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DESIGN STUDY OF A TACTILE CUING SYSTEM FOR PILOT TRAINING

J. W. HILL

K. W. GARDINER

J. C. BLISS

Stanford Research Institute

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FOREWORD

This study represents a portion of the research and development program of the Training Research Division, Air Force Human Resources Laboratory (AFHRL), Wright-Patterson Air Force Base, Ohio. The report covers the research conducted by the Stanford Research Institute, Menlo Park, California under Contract F33615-68-C-1435. The Work Unit 171003021, Design Study of a Tactual Cuing System for Pilot Training, is documented under Task 171003, "Human Factors in the Design of Systems for Operator Training and Evaluation," of Project 1710, "Human Factors in the Design of Training Systems."

Dr. James C. Bliss, Manager of the Bioinformation Systems Group, Engineering Sciences Laboratory, Stanford Research Institute, was the Principal Investigator. Dr. Gordon A. Eckstrand, AFHRL, was the Project Scientist. Dr. Melvin S. Majesty, Lt Col, AFHRL, was the Task Scientist.

While the authors are responsible for the material contained in this report, the contributions of other individuals are acknowledged as follows: C. A. Weihl, who conducted the training experiment and processed much of the data; B. M. Wilber, who wrote the LINC-8 computer programs for monitoring the performance of the subjects; K. H. Kerwin, II, for gathering data for Section II; and A. F. Ferrera, who built the interface circuitry and kept the facility operating.

This report, which was submitted by the authors in July 1969, has been reviewed and approved.

GORDON A. ECKSTRAND, PhD
Chief, Training Research Division
Air Force Human Resources Laboratory

ABSTRACT

Several vibrator, air jet, and moving-button tactile stimulator-units were evaluated as cuing aids for pilot training in a manual tracking task. The best units, as determined by minimum mean square error and best operator describing function were built into a flight simulator. These units were further evaluated for their ability to help pilots control the trainer in some flight-simulation tracking tasks such as altitude holding and ILS landing. A one-dimensional tactile cuing system was designed using information obtained from these experiments. The cuing system, which consisted of two vibrators attached to the arms indicating heading error in excess of five degrees, was tested in a controlled experiment with four pilots having less than 200 hours of flight time. The two pilots using the cuing system learned significantly faster than the two pilots not using the system. This increased learning rate, however, was only seen when the pilots were engaged in side tasks such as problem solving and the taking of clearances. Plans for a more complete test of this cuing system and for possible extensions of the cuing system to other aircraft variables are suggested. A selected review of the literature and current research was carried out to assess the feasibility and appropriateness of biostimulation and bioelectric control for pilot training and aircraft control.

SUMMARY AND CONCLUSIONS

PROBLEM

Air Force activity in this area dates back to the early 1950's when a tactual sensory control system was studied in the context of aircraft guidance. Current technological advances and the results of recent laboratory investigations at a number of universities and under military-sponsored research have suggested that knowledge about tactual communication has advanced to the point at which the design of a complete tactual cuing system is feasible and practical. Sensory modalities other than vision and hearing provide relatively uncluttered information channels for supplementing or complementing the more heavily used receptor channels. At the present time the visual and aural senses of the pilot are employed to very near, if not in excess of, full capacity. Efforts to relieve these two senses and add to flying efficiency, as well as safety, have been accomplished primarily within the same sense modality. Adding additional indicators to already saturated instrument panels and visual requirements, or adding additional override circuits to the auditory composite, may be adding as much noise as signal to the information flow. The use of the uncluttered tactual channel may afford an opportunity to improve pilot training as well as unburden the visual and auditory channels. The value of tactual cuing for pilot training, flight safety, and operational performance appears promising but it is relatively an unexplored area.

APPROACH

The major goal was to design a tactual system and to establish an experimental design to assess its performance. A review of the status of technology showed that to produce a useful design would require extensive experimentation. The results of previous work in tactual stimulation were not in a flight context and could not be directly applied to flying without a serious over-extension of the state-of-the-art. Therefore, an experimental program was initiated. The strategy was to start with a number of promising possibilities, identify the most attractive of these through preliminary experiments, and then refine the choices with more extensive experimentation. Tactual research facilities, utilized in support of Air Force and NASA research requirements over the past five years, were coupled with a flight simulator, i.e., a General Aviation Trainer (GAT-1).

RESULTS

Tactual cues seemed to be neglected in favor of the primary visual instruments until the pilot became overloaded. Without side tasks (free flight condition) it made no difference whether or not tactual cuing was used. With the most difficult side task (clearances) the difference was maximum Tactual cuing was important mainly when the pilot was loaded with work that keeps him busy while he has to control the aircraft.

CONCLUSION

Although the tactual system employed in this study was uncomplicated and very inexpensive, the state-of-the-art of tactual systems in the context of pilot training has not advanced to the point where a design for a tactual cuing system can be developed without qualifications. However, if the Air Force wants to develop and test a tactual cuing system to take advantage of the learning acceleration reported in this study, a two-stage experimental design is recommended.

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SECTION I

INTRODUCTION

This report describes the results of a one-year study on the potential effectiveness of haptic (or tactile) communication in the training of Air Force pilots. The purpose of the research was to find ways to enhance the undergraduate pilot training program by supplementing or complementing the visual and auditory senses. The general objectives of the project were as follows:

(1) To study all factors relating to a haptic system from the sensory, perceptual, flight-control, and training standpoints.

(2) To identify those aspects of flight control and pilot training for which haptic communication is most appropriate, feasible, and effective.

(3) To review, evaluate, and describe existing haptic communication aids, devices, designs, and patents.

(4) To design a complete haptic system to supplement or complement the visual and auditory senses as used in learning how to fly.

(5) To prepare an experimental design that will assess the value of the haptic system for training purposes and specify the criterion data to be collected.

In this report Section II deals with Items 1 and 2 above, and Section III deals with Item 3. While the major goal of the project was to produce a design of a haptic system and an experimental design to assess its value, the results of the review of existing haptic communication aids clearly showed that to produce a useful design would require extensive experimentation. While several related previous projects have been described in the literature, the results of these projects did not answer most of the questions involved in the design of a haptic system for pilot training. We therefore embarked on the experimental program described in Sections IV, V, and VI.

The range of possibilities for haptic cuing in pilot training is large--much too large to be exhaustively tested in a one-year program of this magnitude. Therefore we were required to follow a strategy of starting with a number of promising possibilities, finding the most attractive of these with preliminary experiments, and then refining the choices with more extensive experimentation. Throughout, we used the computer-based facilities for tactile research that we have developed over the past five years under Air Force and NASA support to quickly set up, run, and analyze results from the various experiments. The prior existence of these facilities together with the addition of the General Aviation Trainer (GAT-1) during the project greatly enhanced this research.

Finally, in Section VII we describe a design for a haptic system for pilot training (Item 4, above), and an experimental design to assess its value (Item 5, above). As the reader will discover, these designs were arrived at through the process of careful experimentation and objective evaluation.

SECTION II

SELECTION OF FLIGHT-TRAINING TASKS FOR HAPTIC COMMUNICATION

1. AIRCRAFT FLIGHT PROCEDURES

A careful review of the undergraduate pilot-training (UPT) flight procedures as outlined in Syllabus of Instruction for Undergraduate Pilot Training (Nr. P-V4A-A) was made and the many detailed flight-training procedures were categorized and evaluated for the application of haptic cuing. The main categories selected encompass the UPT curriculum, and these categories are outlined below.

The operation of an aircraft, insofar as the role of the pilot is concerned, can be divided into the three general categories: ground procedures, contact flying, and instrument flying. Typical elements contained within each of these categories are listed below:

(1) Ground Procedures

(a) Flight Planning

- Course layout
- Weather briefing
- Weight, fuel, performance calculations
- Flight-plan filing

(b) Preflight Inspection of Aircraft Exterior and Engine

(c) Cockpit Check of Instruments, Radios, and Auxiliary Systems

(d) Engine Start

(e) Taxiing and Ground Maneuvers

(f) Engine Run-Up and Controls Check

(2) Contact Flying Procedures

(a) Take-Off Roll and Transition

(b) Landing Flare, Touchdown, and Rollout

(c) Ground Reference Maneuvers

- Airport traffic pattern
- Following a road or river
- S-turns across a road
- Orbiting of a fixed point
- Eights on pylons

(d) Airwork

- Straight and level flight
- Coordinated turns
- Climb and descent
- Climbing and descending turns and spirals
- Stalls
- Slow flight
- Aerobatics

(e) Formation Flying

- Maintaining position
- Changing position

(f) Emergency Procedures

- Power failure
- Aborted landing

(3) Instrument Flying Procedures

(a) Control, via reference to instruments, of:

- Attitude
- Altitude
- Airspeed
- Heading

(b) Procedure Maneuvers

- Climbout and departure
- Enroute change of heading and altitude
- Holding patterns
- Area approach and letdown procedures
- Landing approaches

(c) Navigation

- Position fixing
- Course following and off-course
- Reporting
- ATC traffic-control procedures.

2. METHODOLOGY USED TO SELECT TASKS FOR HAPTIC CUING

The methodology developed for the selection of flight-training tasks suitable for the application of haptic cuing is represented schematically in Fig. 1.

The first step in determining whether haptic cuing could be applied to a given flight-training procedure or maneuver was to assess whether a suitable sensing and reference system existed that could provide control information for the tactual stimulators. No instrumented reference system is readily available for many of the functional categories in the flight-training outline. It is, of course, possible to consider the instructor-pilot as such a reference system and to permit him to sense, judge, and then to control the tactual stimulators. This alternative is considered separately and discussed in Sec. II-4.

Visual references outside the cockpit, in a traffic pattern for example, may provide a quantitative measure of performance, but this information is not readily accessible in instrumented form for generating a reference signal. The task of flying inbound on an ILS localizer, on the other hand, admits of a reference signal that is both quantitative and accessible. Other suitable references are provided by autopilot systems, flight instruments, navigation instruments, or special-purpose instrumentation.

Given an instrumented task, there is a choice of presenting the entire range of this variable tactually or of selecting a desired performance value and presenting tactually only small variations (errors)

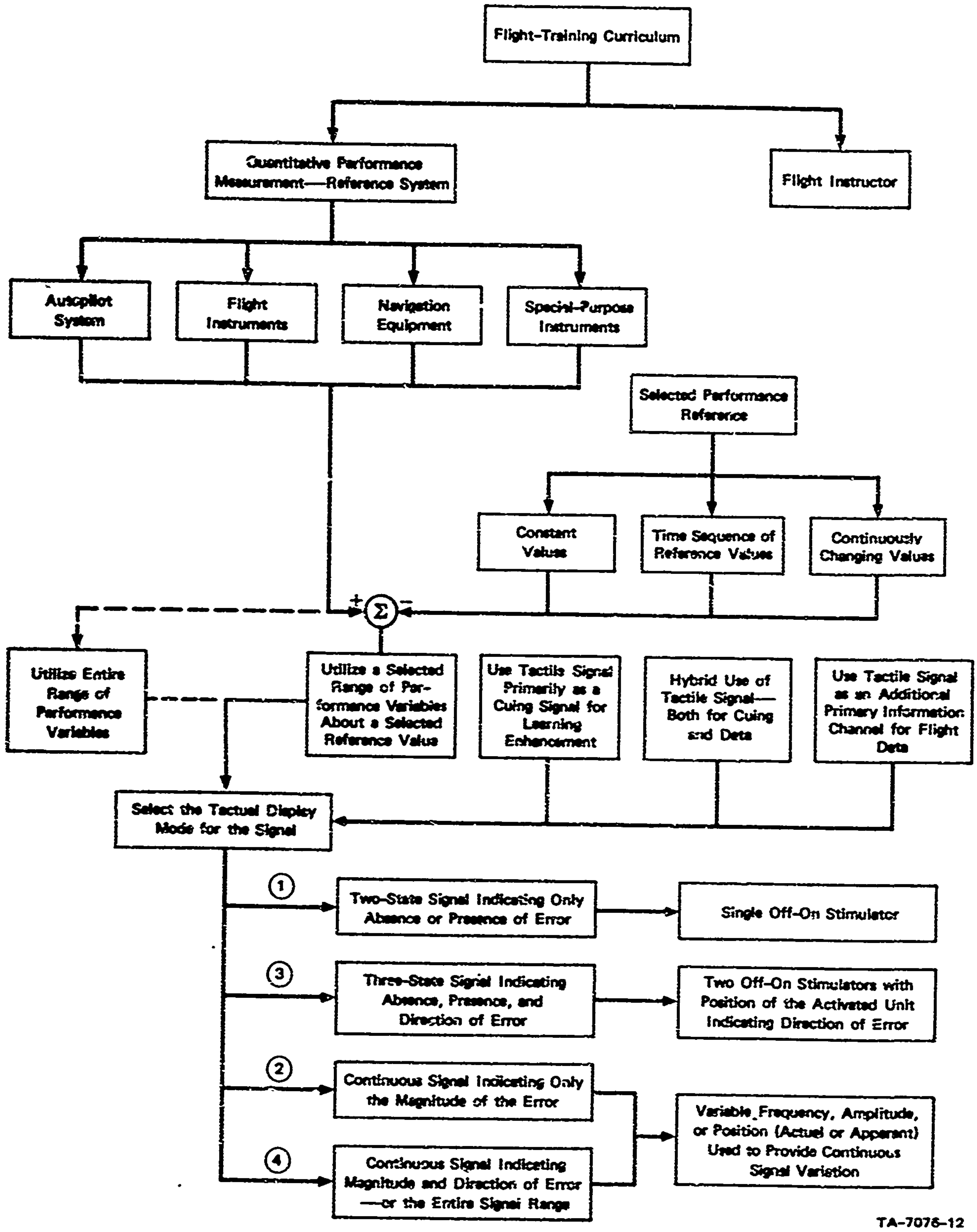

Figure 1 Flow Chart for Selecting Flight-Training Tasks for Tactile Cuing

about this selected value. The tactual presentation of the deviation or error signal from a selected reference value was the method chosen, because of the wide range of many of the instrumented parameters (airspeed, altitude, heading, etc.), and the limited resolution of the tactile channel.

The tasks chosen for testing were ones in which the selected performance reference value remains a constant--for example, hold a constant altitude while executing a variety of other assigned tasks, such as going from cruise configuration to slow flight and the reverse.

Once the value of tactual reinforcement is established using tasks where a constant reference value can be used, consideration can be given to the wider class of maneuvers that require a changing reference value.

The selection of the tactual display mode is influenced by the basic use chosen for the tactual signal. Two uses can be isolated: First, the tactile channel may be used purely as a teaching aid--that is, to reinforce techniques that have already been learned. Second, the channel may be used purely for transmission of new or back-up information. A combination of these two techniques may also be useful.

The use of the first two display modes would be limited to a reinforcement application. For example, presenting existence and/or magnitude of error, but not direction, forces the student to look at the appropriate instrument(s) to take corrective action when the magnitude of the error is sufficiently great to warrant his attention. This will both reinforce his instrument scan and thus aid in enabling him to learn to divide his attention properly, an important and often difficult task to master.

The third and fourth modes reinforce and also provide a primary or back-up channel of information. For example, during a visual approach to landing, the pilot's attention should be centered outside the aircraft; yet, the airspeed is a critical parameter that should be maintained at a selected value. The tactile presentation of the airspeed variation from the selected approach value could reduce the number of times the pilot would need to divert his attention to look at the instrument panel during an approach, and provide him a continuous indication of airspeed to enable a more precise and safe approach to be made.

3. EXPERIMENT DESIGN

Three different experiments were designed for testing these ideas. All three used signals available on the instrument panel as their reference. From the selected instrument simulation circuitry an expanded part of the instrument scale is presented using the third and fourth modes described above. A short description of the experiments is given below.

a. Altitude Holding

This experiment compared several displays on an altitude-holding task. In each test the pilot attempted to hold his altitude constant at 1000 feet and his heading constant at 270°, while following a time schedule requiring him to change airspeed every 90 seconds. On each test, a tactile display presented the altitude deviation from 1000 feet.

b. Altitude Tracking

This experiment compared altitude tracking with and without each pilot's favorite display. The pilot's task was to hold his altitude constant at 1000 feet and his heading constant at 270° for a five-minute run. A pseudo-random command signal added to the GAT-1's altitude made the task fairly difficult. Both altitude and heading cuing were tested.

c. ILS Landing

This experiment measured the pilot's ability to make an ILS landing approach with and without tactile cues. The pilot is instructed to maintain his airspeed at 85 mph during the approach and to stay centered on the beam. Tactile cuing tests, alternately using both airspeed deviations and glide-slope deviations were carried out.

4. THE ROLE OF THE FLIGHT INSTRUCTOR

The role of the flight instructor as indicated in Fig. 1 is as a substitute to interpret the measured performance against the selected performance. This means the instructor would read the selected flight instrument or judge the external visual cues, and compare with the desired performance and then manually operate the haptic cuing system. This is not believed to be a desirable function for the instructor to perform, for two important reasons:

(1) Simple instrumentation can compare the selected value against the measured value accurately, reliably, and with repeatable characteristics. This would be difficult for an instructor to do.

(2) There are many other more important functions that the instructor must perform. Many of these functions could not be performed or would be inadequately accomplished if his attention were required to measure and compare performance.

The following are some of the key functions that the flight instructor must perform:

(1) <u>Instruction in Specific Flying Maneuvers and Techniques</u>

(a) <u>Verbal Descriptions of Training Maneuvers</u>

(i) Explain purpose of maneuver

(ii) Description of maneuver

- Background and relationship of this maneuver to previous maneuver and experience

- New aspects of this maneuver

- Significant points explained in detail

  - Aerodynamic and aircraft motion characteristics

  - Pilot reference systems both instrument and external visual

  - Pilot control techniques.

(b) <u>Flight Demonstration and Shortened Verbal Description to Match and Supplement Demonstration</u>

(c) <u>Assist the Students' Initial Attempts to Perform New Maneuvers</u>

(i) Verbal corrections

(ii) Physical help by instructor with controls if needed

(iii) Further explanation and demonstration in areas of student difficulty

(d) <u>Instructor Must Analyze the Student's Performance and Determine What is Wrong and the Causes Behind the Problems</u>

(i) Failure to understand clearly the maneuver

(ii) Inability to master the execution of the maneuver

- Weak in sensing the aircraft state in the environment and hence unable to determine required control action

- Weak in performing skills
- Inability to combine past experience and present skill level into appropriate responses to new or different situations
- Poor judgment, poor reasoning, under pressure.

(2) Other Tasks

(a) The Overall Command Responsibility for the Safety and Proper Operation of Each Training Flight

(b) The Assessment and Evaluation of a Number of Characteristics and Capabilities of the Student

(i) Overall flying proficiency

(ii) Alertness

(iii) Discipline

(iv) Judgment

(v) Ability to plan ahead and anticipate forthcoming situations

(vi) Retention and previous knowledge and skills

(vii) Sense and apply the appropriate positive and negative reinforcements when needed, as determined by the student's performance and personality.

These are all very significant functions of the instructor and are applied to both the detailed maneuvers and technique of flying and the overall flying performance of the student. Detailed interactions of the student and instructor occur that can be both beneficial and detrimental to the progress of the student.

It is not at all clear that tactile reinforcement or communication would be useful to the student, or to the instructor in performing these functions. Therefore the tasks for evaluating tactile reinforcement and data communication were selected from those with an instrumented reference, as outlined in Fig. 1.

5. CONCLUSION

The wide diversity of maneuvers involved in flight training results in continually varying references for judging student pilot performance. Three maneuvers related to instrument flight training were selected for the haptic cuing tests in the GAT-1 simulator. While the results from specific experiments were encouraging, the specific tasks so instrumented are a very small part of the overall training curriculum. To implement a significant part of the curriculum would require a complex reference system to meet the variety of demands placed on it. Haptic cuing would therefore have a greater effect on flying as a basic information channel rather than a learning-reinforcement channel. However, its value in either or both of these roles can be determined only through careful, unbiased experimentation.

SECTION III

SURVEY OF LITERATURE ON TACTILE DISPLAYS

A literature survey was conducted to find the most pertinent studies on the use of tactile displays in vehicle-control tasks. The results are shown in condensed form in Table I. Although only two of the references* discuss direct applications to the control of aircraft, the majority are general studies of tracking behavior with tactile displays and can also be considered for use in aircraft control functions.

The references describe a wide range of tactile display systems, but unfortunately most investigators used means of evaluating their displays that are either unrealistic or do not allow comparisons. For example, experiments that use predictable single-sine-wave command signals are not realistic, in that these laboratory tests cannot be used to predict real-world results, where the perturbing influences are invariably random and unpredictable. Also, a difficulty with most of the older work is that it relied only on mean square error for performance measurements. While this is a rough but adequate measure for comparing performance within a given experiment where command-signal bandwidth and amplitude as well as vehicle dynamics are constants, it is not satisfactory for comparing displays evaluated in experiments where these parameters are all different. The recent use of describing functions practically ends this ambiguity because the gain and time delay of an operator using a given display can be determined more or less independently of these other variables.

In spite of these difficulties the information in Table I may be partially applied to understanding the importance of the main variables in the design of tactile displays for pilot cuing. The results regarding the main variables (locus of stimulation, stimulus variable, and display algorithm) are discussed separately below.

1. Locus of Stimulation. Most of the previous studies placed the tactile display on the hand. In particular, Wissenberger and Sheridan (1962) found that mounting the display on the skin surface that moves the control stick provides better performance than mounting the display on the opposite hand. This suggests that a good location for a display is on the control stick. Other studies have obtained fair results using the chest and forehead. In a controlled experiment using describing functions, Bliss (1967) showed that the same display on the forehead and on the hand gave equal performance. In general this problem has not been well studied and no clear-cut guidelines have been established.

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*References are listed at the end of the report.

Table I

ANNOTATED BIBLIOGRAPHY ON TACTILE DISPLAYS FOR TRACKING

Reference	Displays	Command Signal	Measure	Notes
Ballard and Hessinger (1954)	Four vibrators mounted on thumb, each driven at one of three frequencies (two-dimensional control).			No evaluation described. System proposed for aircraft control.
Howell and Briggs (1961)	Three vibrators on chest. On-off control with center vibrator indicating "on target."	Single sine wave (0.02 to 0.25 Hz)	Error power	Vibrotactile and similar quantized visual display gave similar performance. Quickening improved performance but apparent motion was not effective.
Durr (1961)	Five vibrators mounted on chest in "+" pattern (two-dimensional). Interrupted on-off control with center vibrator indicating "on target."	Single sine wave (0.02 to 0.3 Hz)	Error power	Found that magnitude information added to the display by increasing the interruption rate proportionally to the error had no effect on performance.
Weissenberger and Sheridan (1962)	Kinesthetic force from small control stick held between thumb and index finger (linear control).	Sum of 5 sinusoids (0.3 to 1 Hz)	Closed loop describing function.	Better performance obtained when information was sensed at location where the manipulated object is grasped rather than at a separate location.
Hirsh and Kadushin (1964)	Two on-off vibrators on thumb and index fingernails of hand holding control stick.	Steps of random size and polarity.	Integral of absolute error.	Presentation of rate-of-error information tactually and error information visually reduced the visual-error scores a small (7 percent) but statistically significant amount. Two-dimensional presentation of the same information confused the subjects.
Pliss, Brody, and Lane (1966)	Thirteen on-off air jets in a linear array on the back of the index finger and hand holding the control stick. Command proportional to distance from center jet to the jet activated.	Steps of random size and polarity (pursuit tracking).	Fitted a set of operator models to data.	Tactile display movements were slower than visual; however, reaction times with both a tactile and similar visual display were faster than either display alone.
Seeley and Bliss (1966)	7-by-7 square array of air jets on 1/4-inch centers positioned on face (two-dimensional control). Error proportional to distance from center jet.	Sum of 8 sinusoids (0.05 to 2 Hz) sent through different low/pass filters.	Mean square error.	Both tactile and quantized visual displays give very similar results over a range of common bandwidths and display gains. Directional information more important than magnitude information in quantized displays.
Fenton (1966)	Kinesthetic force from a moving button mounted in handle of control stick.	Continuous spectrum (0 to 0.2 Hz)	Mean square error.	A tactile display giving headway information greatly reduced headway variation in a car following. The addition of quickening made the display more effective.
Bliss (1967)	Continuously movable air jet positioned on forehead and palmar side of hand.	Sum of 8 sinusoids (0.02 to 2 Hz).	Describing function and remnant (open loop).	Both forehead and hand displays gave equal performance. With tactile continuous displays operators have less gain than with visual displays but have the same bandwidth.

2. Stimulus Variables. A survey of the classical tactile stimulus variables is given by Geldard (1961), who describes the range of each and some possible applications to tracking. Most investigators have used location as the stimulus variable. In fact this is the only way in which two-dimensional tracking has been carried out. In their binary two-dimensional displays, both Durr (1961) and Hirsh and Kadushin (1964) found some confusions in interpreting the display correctly. Using a much-finer-grained two-dimensional display, however, Seeley and Bliss (1966) found no such difficulty. Another successful variable is kinesthetic force as used in the displays of Weissenberger and Sheridan (1962), and Fenton (1966). Here, kinesthetic force is used as a variable-intensity stimulus. Tests of the variable-frequency display of Ballard and Hessinger (1954) have not been discussed in the literature, so its usefulness is unknown to us. The most promising variables of those previously used appear to be location and intensity.

3. Display Algorithm. Most displays have been linear in that the displayed variable is proportional to the error signal. The chief nonlinearity has been due to quantization (e.g., only a few levels of error information are presented). Earlier displays were binary (quantized into two levels—e.g., right-left) with possibly a separate "on-target" signal. The resulting performance fell short of that obtained with continuous displays. This shortcoming is predicted by the work of Rund, Birmingham, Tipton, and Garvey (1957), and Hunt (1964), who compared visual tracking with and without various degrees of display quantization. Later tactile displays with continuous or finely quantized presentation produced better tracking performance. Few experiments with other nonlinear displays have been carried out.

Because so much of the previous data is difficult to compare, we decided to perform some preliminary display experiments using both mean-square error and describing-function analyses. The first tests were run using various display algorithms and body locations using two variable-intensity vibrotactile transducers. This enabled some of the earlier work using two stimulators to be compared with later displays. There are two main advantages to using the two stimulator displays: (1) the hardware necessary to run the display is minimal and (2) there is high stimulus-response compatibility. The interpretation of the display is straightforward, in that a separate and unique action is dictated by each vibrator.

In addition, a new ripple-tracking air-jet display was tested using the same analysis methods. The display seemed promising for flight control because of the combination of stimulus variables it presented. The ripple display was designed to produce sensations of changing intensity, position,

rate, and possible apparent motion. Experiments were designed to test for the effect of different body locations, display gain, and cycling times. These basic evaluation experiments and their results are described in the next section.

SECTION IV

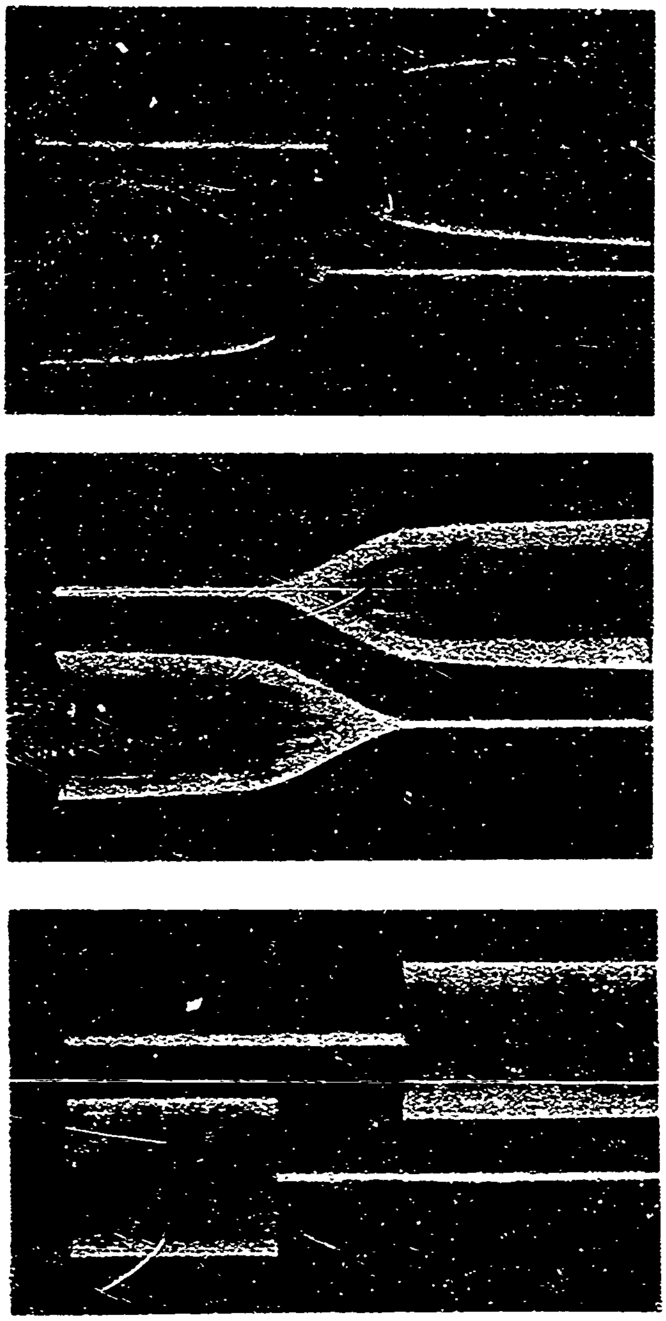
PRELIMINARY DISPLAY EVALUATION

Several tracking experiments were run to determine the trade-offs between the many parameters of tactile displays. Comparisons between different displays, gains, presentation algorithms, body locations, and update rates were carried out in a laboratory manual-tracking task run by the LINC-8 computer system. A tracking program (Bliss, Hill, and Wilber, 1968, Chapter 10) generates the sum-of-sinusoids command signal, accepts the joy-stick position signal, simulates the test vehicle, and computes the resulting error signal for the display. In addition, the program performs an on-line Fourier and power analysis of the error and vehicle position signals in the compensatory tracking task. The advantages of this system are its flexibility in tailoring the task (e.g., the command signal or vehicle dynamics) and speed of obtaining performance parameters after a test run.

Two basic types of displays were tested in these preliminary experiments. They were a two-vibrator display, capable of presenting a continuously varying intensity signal, and a seven-point on or off air-jet display, which was used to present a bidirectional signal quantized into four levels of signal strength. In all these evaluation experiments the test subject was seated at a table and provided with a display, and his task was to move a joy stick in his right hand to keep the displayed error nulled. The integrating test vehicle (i.e., K/s dynamics) was chosen because it closely approximates several of the control actions in an airplane.

The LINC-8 program was used to evaluate three intensity algorithms, each using two vibrators mounted on the arms of the test subject. The three algorithms were (1) linear--no vibration for no error, and vibration increasing linearly with error on one vibrator when the error was positive and on the other vibrator when the error was negative, (2) differential--equal vibration amplitudes with zero error, and a linear unbalancing (up to 0 to 100 percent, or 100 to 0 percent) with increasing positive and negative error signal, and (3) threshold--no vibration within a symmetrical error band and maximum vibration when the error was outside of this band. These algorithms are illustrated in Fig. 2.

A new air-jet ripple-tracking display was also evaluated using the same tracking program. The jets are mechanical stimulators pulsating at 150 Hz and producing pressure pulses of about 1-psi amplitude. The error was presented to the subject by a linear array of seven jets on the back of the left index finger and hand with the center jet of the array positioned over the first knuckle. The timing of the display was similar to the Thunderbird automobile tail-light turn signals, but with inward sequencing of the stimulators instead of outward.



(a) LINEAR ALGORITHM

(b) DIFFERENTIAL ALGORITHM

(c) THRESHOLD ALGORITHM

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Figure 2 Three Types of Tactile-Display Algorithms

1. EVALUATION OF TWO-VIBRATOR DISPLAY

a. Equipment

(1) Tactile Stimulators

For preliminary experiments, two vibrotactile transducers were constructed by modifying two Jensen B4K7 loudspeakers. The speaker driver units are held against the skin of the upper or lower arms or the wrist with an elastic strap of adjustable tension. The contact to the skin is through a 5/8-inch-diameter metal disc. When in contact with the skin, the moving parts are enclosed and very little audible signal results.*

In addition, a laboratory vibrotactile transducer was modified to serve in the preliminary tracking experiments. The transducer consists of two plastic driven pins 0.040 inch in diameter protruding through 0.080-inch holes in a metal plate. The spacing of the pins is adjustable down to 0.1 inch. The unit is capable of stimulating two points on the palm, along a finger, or on a single fingertip.

(2) Display Generator

A display generator was modified to provide a variety of feedback algorithms for two vibrotactile stimulators. The input signal is the error voltage, and the output signals from two power amplifiers drive two separate electromechanical transducers. A separately connected oscillator controls the frequency of the vibratory stimulators. The circuitry of the display generator consists of an analog multiplier, two voltage comparators, and a number of operational amplifiers. A particular display algorithm is obtained by plugging a prewired plug into a control socket on the generator.

The generator has three different algorithms available, each with four different display gains. The three different algorithms are shown in Fig. 2. Here the driving voltages of two tactile vibratory stimulators are shown as a function of error voltage. The horizontal scale in Fig. 2 is one volt per major division. The zero-error condition coincides with the major vertical axis. All three display algorithms have their full-scale deflection (or vibrator full on, the other off) with a one-volt error signal. These same three display algorithms are available with 1/4, 1/2, 1, and 2 volts full-scale deflection.

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*These transducers are shown in Fig. 17 as they were used in a later experiment.

b. Experiment I--Variable Body Locations

(1) Design

In order to find the most appropriate body areas for mounting tactile stimulators on a pilot, a tracking experiment was set up using the display generator to power tactile stimulators on a variety of different body areas. The subject's task in the experiment was to maintain the position of a vehicle (a single integrator in this case) that was additively under the influence of a pseudo-random command signal generated by the computer and a joy stick controlled by the subject.

The command signal generated by the LINC-8 computer consists of a sum of ten sinusoids of equal amplitudes at frequencies shown in Table II. The initial phases of all frequency components is zero degrees and the length of the run is two minutes. In all of the tactile

Table II

COMMAND FREQUENCIES OF PROGRAM TR12/6

Component	Frequency (Hz)
1	0.0167
2	0.0250
3	0.0417
4	0.0584
5	0.0920
6	0.108
7	0.142
8	0.242
9	0.358
10	0.508

tracking runs the display generator was programmed to give the response shown in Fig. 2(a) with a modulation of 100 Hz and a 1/2-volt full-scale deflection. In addition to the tactile experiments, a visual tracking experiment was run to establish a limit on the subject's ability to track the command signal. With each subject the following six tracking runs were made:

Run 1: Visual tracking using a horizontal line on an oscilloscope to represent the position of the vehicle. The scope vertical sensitivity was 0.5 volts/cm.

Run 2: Tactile tracking using two separate speaker transducers mounted on the left and right forearms with elastic straps.

Run 3: Same as Run 2 except transducers were mounted on the upper and lower left arm, well above and below the elbow.

Run 4: Same as Run 2 except transducers mounted on upper and lower half of left forearm.

Run 5: Tactile tracking using a two-point transducer mounted on metal plate. The spacing of the vibrator tips was one inch, so that the left and middle index fingers could each contact a separate vibrator.

Run 6: Same as Run 5 except that the vibrator tips were spaced 1/4 inch apart so that they both contacted the left index fingertip.

(2) Results

The subjects' tracking abilities were measured in terms of the average error power over the two-minute run. If the joy stick were untouched, the error power would be that of the command signal. If the subject interprets the display often and correctly, the error power will be less than that of the common signal. On the other hand if the subject is frequently confused by the display, the error power will be the same or even greater than that of the command signal. Thus, the smaller the error power the more effective the display. The resulting error power normalized to the command signal power for the six tracking runs for three subjects is shown in Table III.

Table III

ERROR POWER IN UNITS OF COMMAND SIGNAL POWER

Run	Subject			
	JH	KE	JC	Average
1. Scope	0.21	0.36	0.23	0.27
2. Two Arms	0.42	0.49	0.84	0.58
3. Left Arm	0.46	0.48	1.23	0.73
4. Forearm	0.62	0.49	0.87	0.66
5. Two Fingers	0.41	0.48	0.88	0.59
6. Fingertip	0.47	0.37	1.08	0.64

Besides visual tracking, on which subjects did the best, the display locations, in order ranging from best to worst error scores, are two arms, two fingers, one fingertip, the forearm, and upper and lower left arm. The error scores from these five tactile display locations were tested for significance with an analysis of variance. The results indicated that the differences between display locations are not significant [$F(4,8) < 1$]. The difference between the scope display and the five tactile displays was similarly tested and the results [$F(5,10) = 2.54$, $p < 0.10$] indicate that there is a 10 percent probability of getting this difference by chance alone. The results of these two tests taken together show that differences in error-power scores are not large enough to draw conclusions about differences between the display locations, and we may assume them to be equivalent.

As far as the subjects are concerned, the two subjects with previous experience (JH and KE) did better than the subject with no previous experience (JC). This difference suggests that tactile tracking proficiency increases with practice as does visual tracking proficiency (McRuer et al., 1965, Fig. 28).

To obtain more information on the efficiency of the 0.5-volt linear display, the combined operator/vehicle describing functions of the tactile tracking runs were computed and plotted in Fig. 3. Since the runs are not significantly different, all 15 runs are averaged together in the figure. The results are very similar to visual tracking data obtained by McRuer et al. (1965), using an integrating vehicle. The magnitude of the combined describing function drops at about 20 dB/decade increase in frequency, and phase shift is minus 90 degrees, dropping off with both the higher and lower frequencies.

Both the magnitude and phase shift of the describing function shown in Fig. 3 have been fitted with the simple crossover model (McRuer et al., 1965, p. 151). The model was primarily fitted in this crossover region (gain ≈ 1.0) of the curves, and there agreement is best. The curves of Fig. 3 indicate the results predicted by the model. The departures from model and theory for frequencies below 0.05 Hz are due to low-frequency operator lags. In the high-frequency region the fit is very good and the estimated equivalent gain, K_e, is 1.90, and the estimated equivalent time delay, is 0.255 second. The difference between visual and tactile tracking performance will be discussed in Sec. III, using these parameters.

c. Experiment II--Two-Vibrator Gain and Cuing-Mode Experiment

(1) Design

This experiment was carried out to compare the linear, differential, and threshold algorithms shown in Fig. 2, using the tracking tasks described in Experiment I. Each of these algorithms was tested at

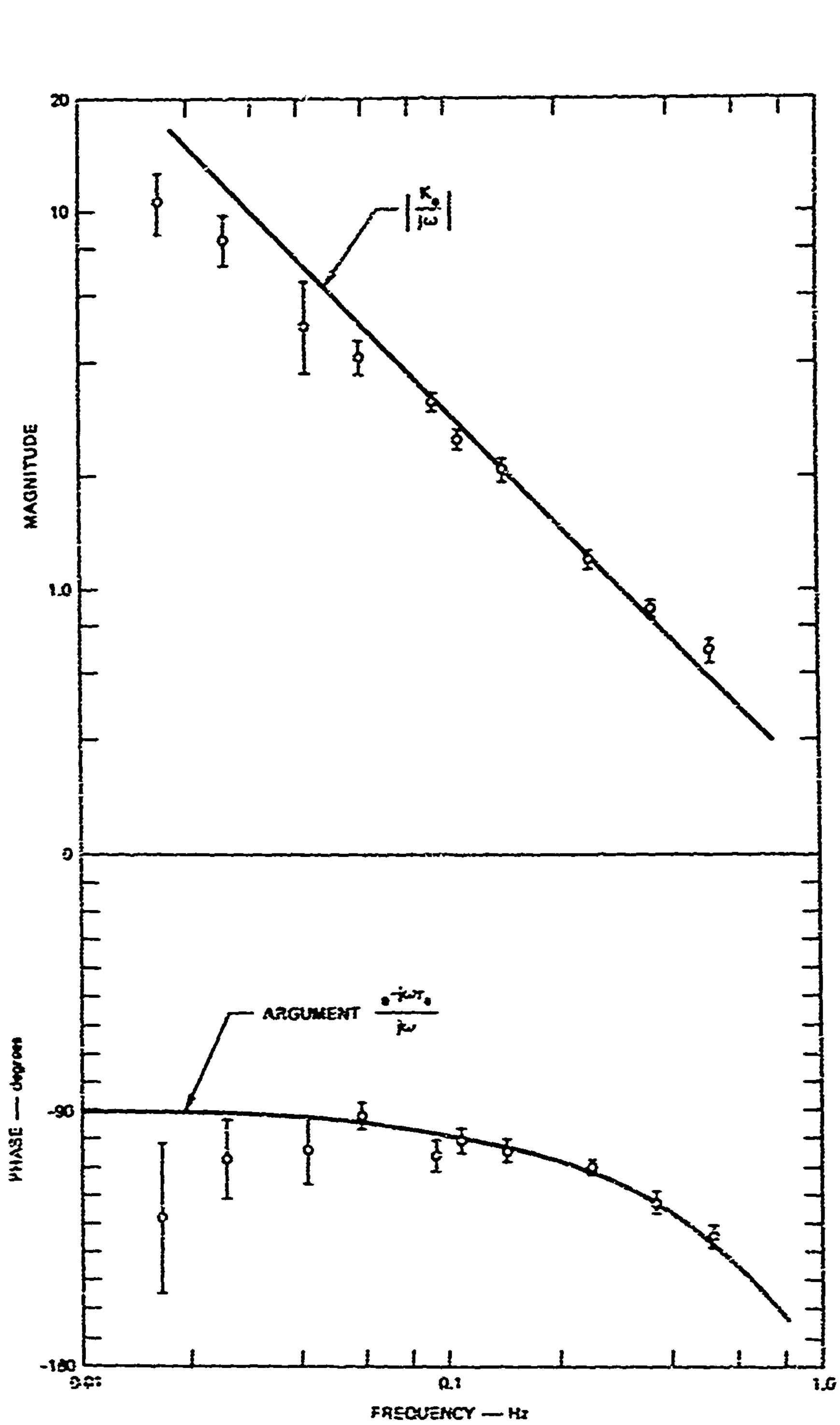

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FIGURE 3 COMBINED OPERATOR/INTEGRATING VEHICLE DESCRIBING FUNCTIONS OBTAINED USING THE TWO-VIBRATOR TACTILE DISPLAY SHOWN IN FIGURE 4. Vibrator intensity was proportional to the magnitude of the error. The data points indicate the mean, and the length of the bars indicates the 2σ ranges for each frequency. The curves represent the simple crossover model fitted in the crossover region.

four different display gains using three test subjects. Each subject had twelve, two-minute tracking runs, one with each algorithm and one with each gain (0.25, 0.5, 1.0, and 2.0 volt for full display range). The twelve runs were assigned each subject in a separate, random order to balance out learning effects over the group of three subjects.

The location of the two speaker vibrators (which were driven at 100 Hz) was always on the left and right forearms. The tracking program described in Experiment I generated the command signal and simulated the integrating vehicle.

(2) <u>Results</u>

The normalized error powers from the experimental test runs are shown in Table IV. In addition, the error-power scores averaged over all three subjects are plotted in Fig. 4. The general trend shown

Table IV

AC ERROR POWER DIVIDED BY COMMAND POWER

	Full-Scale Display (volts)	Subjects			
		JH	KE	JC	Average
Linear Algorithm	1/4	0.49	0.49	0.64	0.54
	1/2	0.64	0.46	0.79	0.63
	1	0.71	0.76	0.97	0.81
	2	1.22	1.08	1.09	1.13
Differential Algorithm	1/4	0.80	0.80	0.94	0.85
	1/2	0.91	0.81	0.88	0.87
	1	1.37	1.25	1.29	1.30
	2	4.02	0.72	3.97	2.90
Threshold Algorithm	1/4	0.83	1.12	1.32	1.09
	1/2	0.72	0.60	0.92	0.75
	1	0.77	0.75	1.06	0.86
	2	4.11	1.00	2.55	2.55

in the figure is toward increasing error power with full-scale display voltages greater than 0.5. The error-power change is variable with smaller voltages (higher gains). To determine the significant variables of the experiment, the data shown in Table IV was given an analysis of variance, the summary of which is given in Table V. The table shows that the different displays are not significantly different, even though the linear-display error power is almost half the error power of the other two displays, suggesting that the linear display is the best.

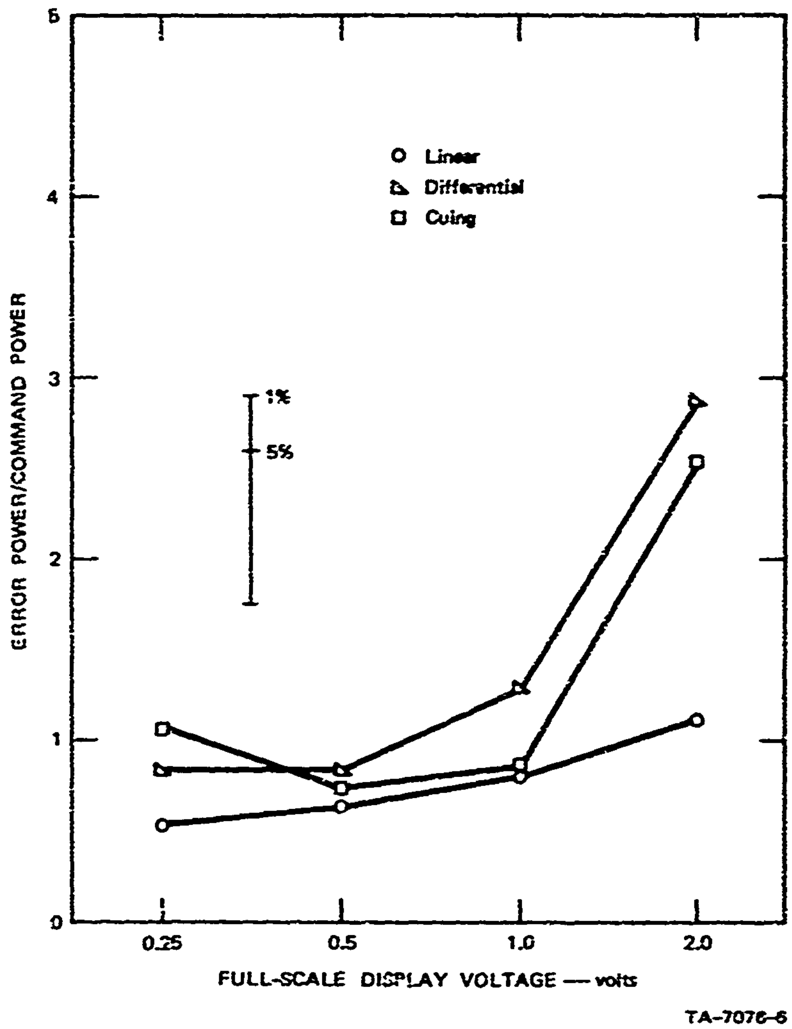

Figure 4 Average Error Scores for the Three Subjects. The tolerance bars are the one- and five-percent t-tests for comparing any pair of data points.

Table V

SUMMARY OF ANALYSIS OF VARIANCE OF THE INDIVIDUAL

ERROR-POWER SCORES

Source	df	Mean Square	F Ratio	Significance
Displays (D)	2	1.6114	3.13	--
Gains (G)	3	4.1359	8.04	$p < 0.005$
D x G	6	0.5081	<1	
Within Subjects	24	0.5153		

The analysis of variance shows that the effect of display gain is very significant. In general the error score is fairly uniform in the 0.25-to-1.0-volt range and increases sharply at 2.0 volts. The average error power for all three algorithms reaches a minimum at the 0.5-volt full-scale voltage.

To further investigate the differences between the three displays, the combined operator/integrating vehicle describing functions obtained using the three different displays with 0.5-volt full-scale deflection were calculated and averaged over the three different subjects. These functions are shown in Fig. 5. Both operator gain and phase shift are plotted at each of the ten frequencies of the command signal. For comparison with visual tracking performance, the visual-tracking describing functions from Experiment I are also included in Fig. 5.

All four of the describing functions are similar as far as shape is concerned. The magnitude of the describing functions drops at about 20 dB/decade increase in frequency. The phase shift is fairly constant at about -90° and rolls off at both the lowest and the highest frequencies. These curves are very similar to the one previously shown in Fig. 4.

The main difference between the curves as far as magnitude is concerned is their varying gain at any constant frequency. At frequencies where the gain is about 1.0, the most stable data points, the gains are consistently ordered from worst to best--threshold, differential, linear, and visual. (The crossover model equivalent gains are 1.19, 1.56, 2.24, and 3.30 respectively.) This ordering indicates that of the three tactile displays, the linear display provides the best overall operator gain within a factor of two of the subject's visual performance. As far as phase shift is concerned, there is very little difference between displays. Visual tracking consistently yields the least roll-off at higher frequencies and the threshold algorithm consistently yields the most, but the difference from best to worst is very small, being 20 degrees at most.

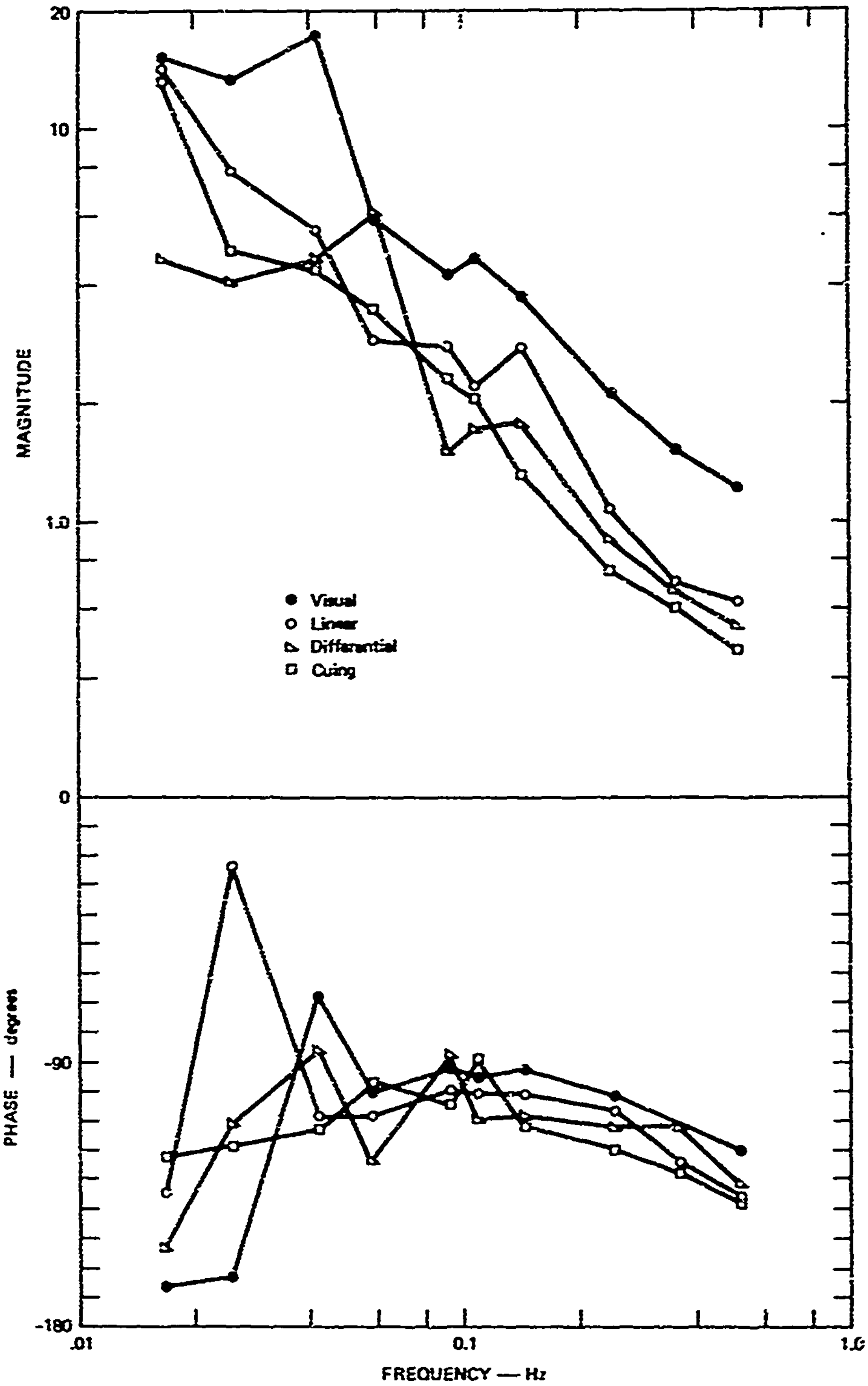

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Figure 5 Combined Operator/Integrating-Vehicle Describing Functions Obtained with the Three Vibratory Displays Compared with the Visual-Tracking Results of the Same Three Subjects

The phase variance at low frequencies is so large that no conclusion about low-frequency performance can be drawn.

The results of both the error-power analysis (though not significant) and the transfer-function analysis agree as to the best and worst algorithms. The best-to-worst ranking, in both cases, is: linear, differential, and threshold.

2. EVALUATION OF AIR-JET RIPPLE-TRACKING DISPLAY

a. Equipment

Following the idea that a tactile display should change along as many dimensions as possible to be more efficient and noticeable, a tactile ripple display was devised and programmed on the LINC-8 computer. The ripple or "Thunderbird tail-light" display produces changes in overall intensity, position, and cycle speed in addition to allowing possible apparent motion at some timing rates.

(1) Hardware

The display hardware consisted of seven air jets from a computer interface allowing the simultaneous activation of up to 96 air jets. Each jet of air was formed by a 0.031-inch outlet nozzle under control of a high-speed electromagnetic valve. The air-pressure pulse, measured 1/8 inch directly above the air-jet outlet, was about 3 psi, with a rise and fall time of about 0.5 ms and an overall pulse width of about 2.0 ms. A 160-cps pulse repetition rate was used throughout the experiments. Thus, when the stimulators were turned on, then pulsated at the 160-Hz rate until turned off. The advantages of air-jet stimulation for this investigation were that relatively uniform stimulation was produced over nonuniform cutaneous surfaces and that stimulator spacing could be easily adjusted.

(2) Software

Two types of displays were tested, one that rippled outward like the "Thunderbird" tail-lights, indicating the direction of the error and another than rippled inward toward the center position indicating the direction of motion necessary to correct the error. The timing of both of these displays with a large error signal is shown in Fig. 6. During timing-interval zero, neither display has any air jets activated. During this time the computer measures the error signal and decides from the magnitude and sign of the error signal the maximum number of jets to activate. In the case illustrated in Fig. 6, the maximum negative error signal was encountered and the displays both proceed through three ac -tional steps. The outward ripple display begins with two jets activated during the next timing interval and adds an additional jet for each additional timing interval until the decided maximum number is reached. he

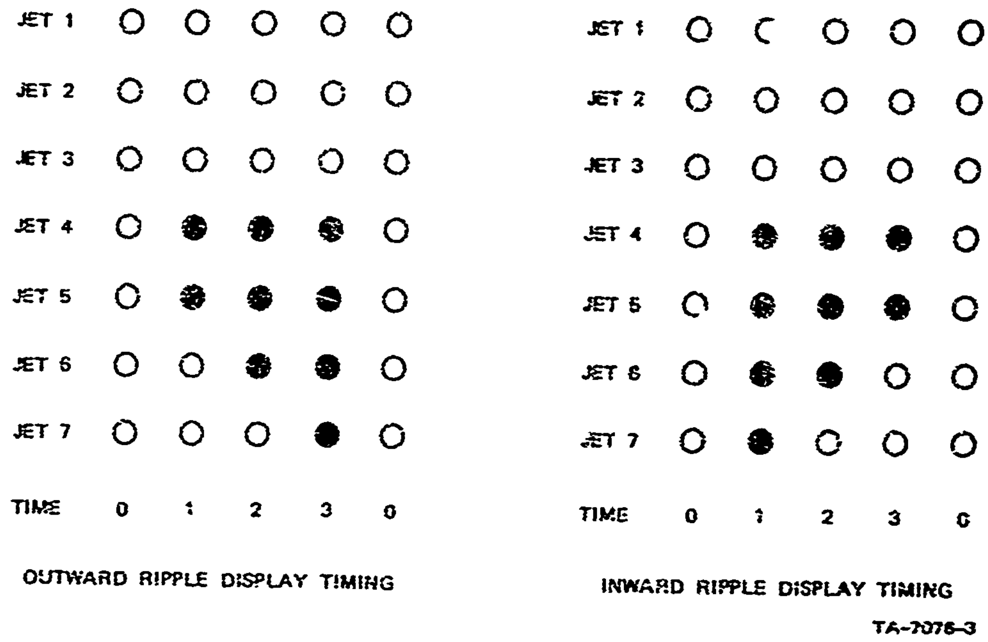

Figure 6 Ripple-Tracking Timing Diagram

inward ripple display begins the first timing interval with the decided maximum number of jets activated and extinguishes one jet at each successive timing interval until two jets are on. The last step in this repetitive cycle is the first in the next--all jets are deactivated and the error signal is again sampled.

This timing sequence is described by three time delays in our ripple tracking program. These delays measured in multiples of sixtieths of a second are defined as follows:

T_1: The duration of the deactivation timing interval

T_2: The duration of the first and subsequent jet-by-jet incrementing intervals

T_3: The duration of the last timing interval in which jets were on.

The conversion between error voltage and the maximum number of activated air jets during the display cycle (display gain) was determined with an interval table. The voltage range between plus and minus 2.5 volts was broken into seven equal intervals. The interval that the error signal is in determines the maximum air-jet position activated during the display cycle. Whenever the voltage is in the largest interval

(which turned out to be 1.78 volts) the display cycle includes the extreme air jet. Whenever the voltage is in the interval centered around zero (within 0.35 volts of zero) no air jets are activated. For comparison with other displays, maximum display indication--full scale--occurs at 1.78 volts.

(3) Preliminary Tests

The two displays were evaluated by allowing subjects to feel the patterns of the air-jet display while the program was operating using a voltage obtained from a joy stick under the subject's control as its input. Thus, subjects could move the stick and judge the appropriateness of the display. The three time delays T_1, T_2, and T_3 were adjustable from three potentiometers on the computer panel while the display was running. The consensus of the few subjects in this informal experiment was that:

(1) The inward-ripple display was much better than the outward display because it showed directly what corrective action was necessary to correct the error rather than just showing the error.

(2) The use of unequal timing intervals did not seem to bring any distinct advantage.

(3) The display would be very useful in transmitting information tactually, and further formal evaluation should be carried out.

b. Experiment III--Variable-Speed Ripple Tracking

(1) Design

The inward-rippling display of the exploratory experiment was incorporated into the LINC-8 tracking program. The command signal had the same frequency components as the previous tracking program, which are given in Table II. The three time delays, T_1, T_2, and T_3, were written into the program so that they would remain accurately known during all the experimental runs. In the ripple-tracking evaluation experiments the seven air jets were positioned over the back of the left hand and left index finger as shown later.* The hand was relaxed and oriented so that the center air jet was positioned over the center of the first knuckle. The subject held the joy stick in his right hand.

*See Fig. 10(a).

Five different tracking programs were compiled, each having a set of time delays differing by a factor of two (approximately) from the others. The time delays used in each of the programs are shown in Table VI in sixtieths of a second. The minimum update rate is the average frequency that the display is updated when either extreme air jet is activated.

Table VI

PARAMETERS OF THE RIPPLE-TRACKING PROGRAM

Program	T_1	T_2	T_3	Minimum Update Rate (Hz)
RPTK 82	1	1	1	60.0
RPTK 62	2	2	1	34.3
RPTK 42	3	3	4	18.5
RPTK 22	6	6	8	9.2
RPTK 12	12	12	12	4.6

The timing of the two programs, RPTK 22 and RPTK 42, was selected to produce approximately 100-ms and 50-ms timing intervals, which are appropriate for producing tactile apparent motion (Kotovsky and Bliss, 1963; Sherrick, 1968). Tactile apparent motion, having a direction and magnitude, could possibly enhance the effectiveness of the display by adding an additional signal dimension. The next-faster and next-slower programs RPTK 62 and RPTK 12 bracket this range and serve as controls, while RPTK 82 cycles through the display timing intervals at the highest rate obtainable (60 Hz).

All of the displays had the same conversion between error signal and maximum air-jet position. Full display indication occurred with an error signal of 1.78 volts.

(2) Results

The evaluation experiment consisted of two test runs on each tracking program by two of the same subjects that participated in the previous vibrotactile tracking experiments. The normalized error power from each tracking run is used as a measure of tracking ability. The smaller the error power, the better the tracking. The normalized error powers obtained from the experiment are shown in Table VII. These data averaged over the two test runs are plotted in Fig. 7 for comparison. The figure shows that the error power decreases monotonically as the update rate of the display is increased. The change in error power with update rate was tested with an analysis of variance and found to be very significant [$F(4,12) = 10.15$, $p < 10^{-8}$]. The error-power results are decreasing even with the fastest program, RPTK 82, suggesting that even

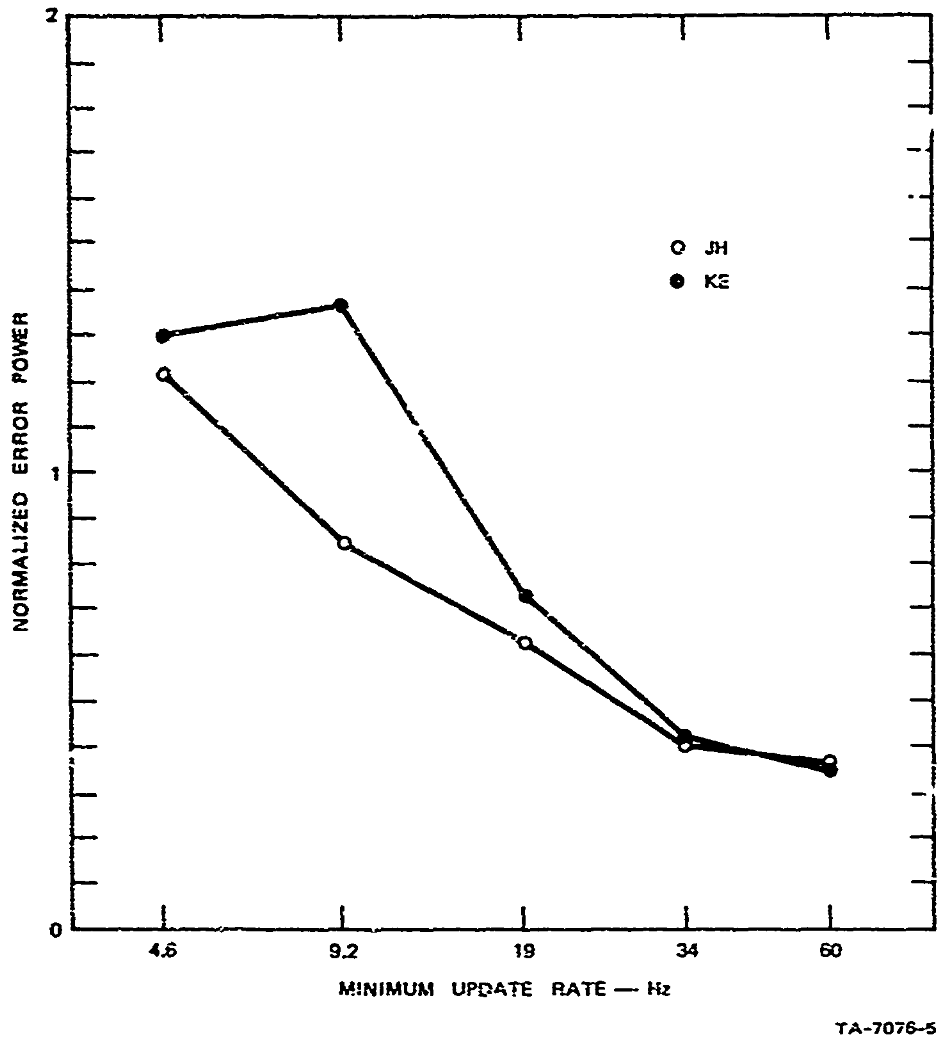

Figure 7 AC Error Power Divided by Command Power as a Function of the Minimum Display Rates of the Five Ripple-Tracking Programs

Table VII

AC ERROR POWER DIVIDED BY COMMAND POWER

Program	Subject			
	JH		KE	
	Run 1	Run 2	Run 1	Run 2
RPTK 12	1.28	1.33	1.47	0.96
RPTK 22	1.88	0.87	0.91	0.[illegible]
RPTK 42	0.79	0.68	0.67	0.58
RPTK 62	0.45	0.50	0.40	0.42
RPTK 82	0.33	0.38	0.34	0.37

faster cycle rates would produce better tracking performance. However, the curves are relatively level at the highest two update rates and their displays are probably providing near-optimum performance.

The hoped-for improvement with the timing rates producing tactile apparent motion (9- and 19-Hz update rates) did not materialize in the experiment. The apparent-motion improvement would have resulted in U-shaped error curves in the area between the 9- and 19-Hz uptake rates in Fig. 7. This type of a dip is not apparent in the figure. Instead, the rule describing the results is: the faster the cycle times, the better the tracking performance.

To better understand the effect of the varying update rates, the combined operator/vehicle describing functions for the five tracking programs were obtained. The results for the slowest, intermediate, and fastest displays averaged over both subjects (four runs for each curve) are shown in Fig. 8. The main differences shown in Fig. 8 are (1) that operator gain increases with display rate, and (2) that high-frequency phase shift decreases with display rate. The combined transfer functions were fitted with the simple crossover model previously described and the results are shown in Table VIII. Inspection of the table shows that the equivalent gain, K_e, increases with display speed but levels off at about 2.2 with the fastest two displays. The equivalent time delay, τ_e, decreases with display speed until it reaches the usual equivalent operator time delays of about 0.12 to 0.15 second with the fastest three displays. The main difference between visual tracking and tactile tracking with the fastest display is the 40-percent gain difference. It appears that the equivalent time delay may even be smaller with the fastest tactile display than with the v' al display.

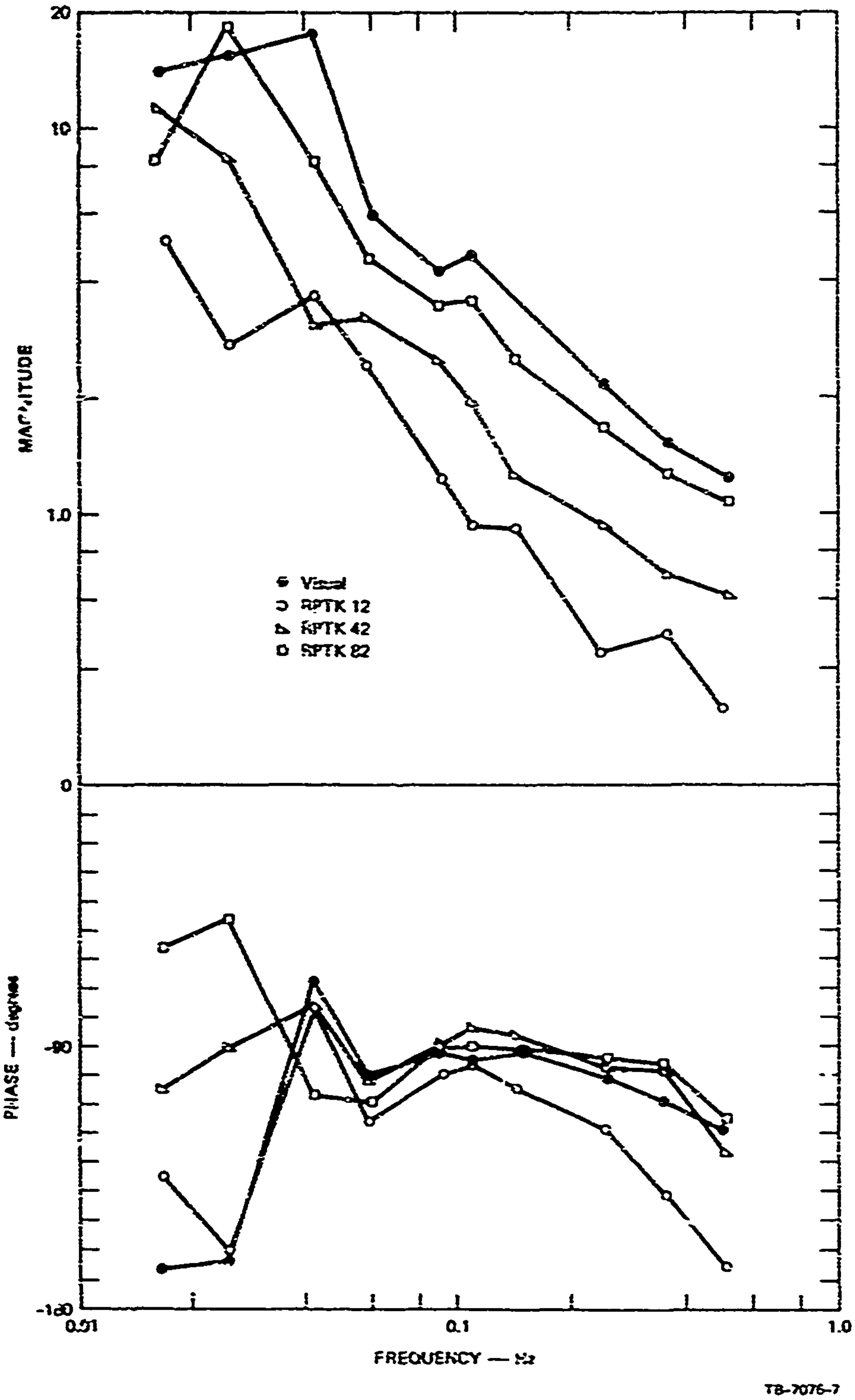

Figure 8 Combined Operator/Integrating-Vehicle Describing Functions for Three Different Ripple-Tracking Displays. Visual data from Experiment I are included for comparison.

Table VIII

SIMPLE-CROSSOVER-MODEL PARAMETERS

Display	K_e	τ_e (s)
RPTK 12	0.69	0.43
RPTK 22	0.92	0.28
RPTK 42	1.27	0.14
RPTK 62	2.20	0.16
RPTK 82	2.25	0.12
Visual	3.30	0.15

c. Experiment IV--Variable-Gain Ripple Tracking

(1) Design

To investigate the effect of varying the gain of the ripple-tracking display, three additional ripple-tracking programs with different gains were compiled using the same command signal and integrating vehicle used in Experiment I. All three additional programs used the fast, 60-Hz update rate that was shown most efficient in that experiment. In total, then, four tracking programs were available with the 60-Hz rate: the previous program, RPTK 82, which produced a full-scale display (four jets actuated) with a 1.78-volt error signal, and the new programs, RTK810, RTK804, and RTK802, which produced full-scale displays with a 0.89-, 0.45-, and 0.23-volt error signal respectively. The three new tracking programs were tested using the same left-hand, left-index-finger air-jet arrangement of the previous experiment (Experiment III). One tracking run was conducted with each version of the program by each of the two subjects participating in the previous experiment.

(2) Results

The normalized error scores resulting from the test runs are plotted in Fig. 9. Although performance is fairly uniform for the smallest three gains shown in Fig. 9, it is best for both subjects with the 0.89-volt program. Comparing programs, subjects reported that with the 1.78-volt program the gain was fairly insensitive and the display would indicate no error for periods of a few seconds duration during the runs. On the other hand, with the 0.23-volt program the gain was so high that the display was only bidirectional, indicating only full right or full left responses most of the time. At the intermediate 0.89-volt gain, both magnitude and direction information were available.

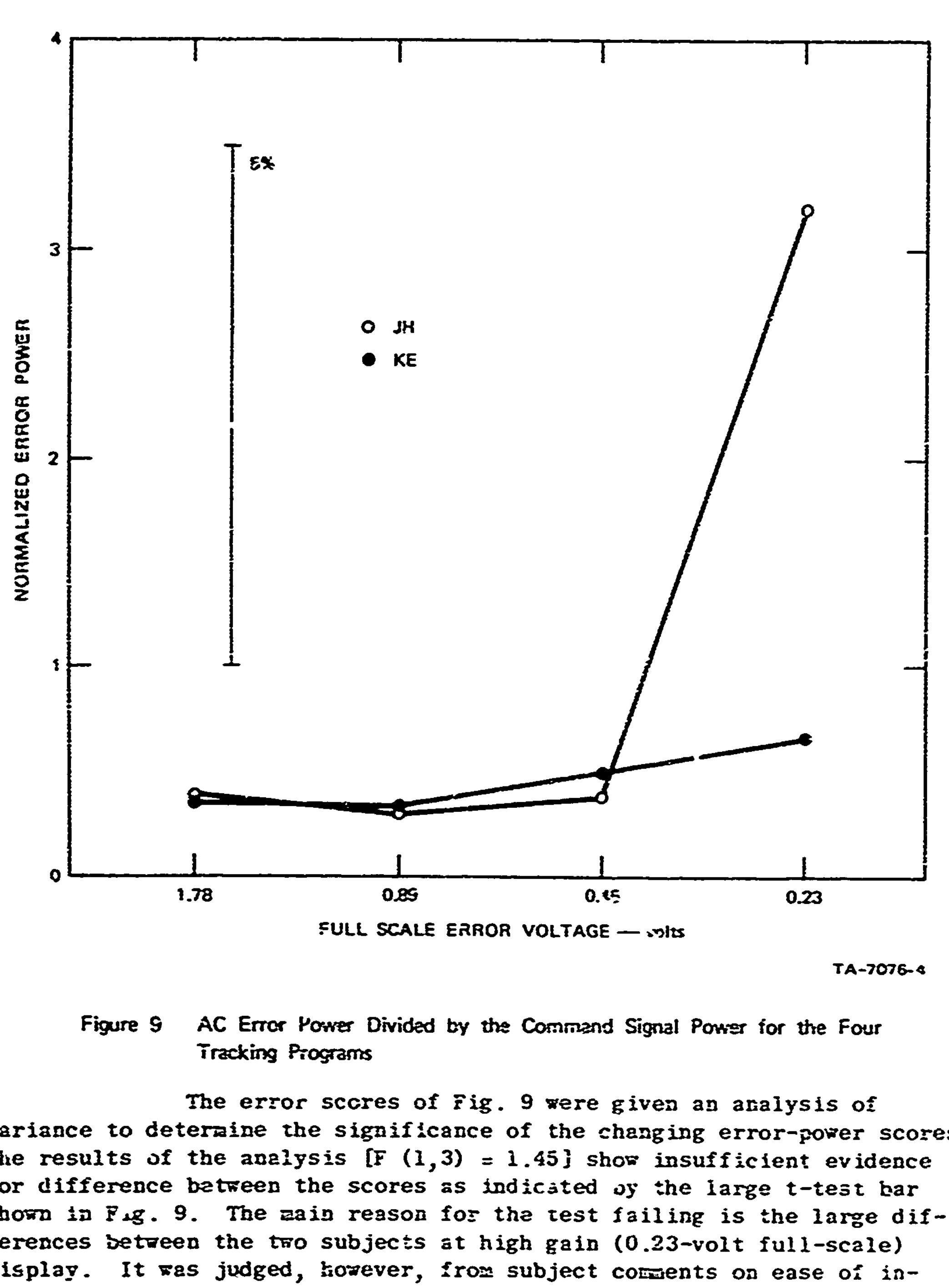

Figure 9 AC Error Power Divided by the Command Signal Power for the Four Tracking Programs

The error scores of Fig. 9 were given an analysis of variance to determine the significance of the changing error-power scores. The results of the analysis [F (1,3) = 1.45] show insufficient evidence for difference between the scores as indicated by the large t-test bar shown in Fig. 9. The main reason for the test failing is the large differences between the two subjects at high gain (0.23-volt full-scale) display. It was judged, however, from subject comments on ease of interpretation and control with the 0.89-volt full-scale display as well as the low error scores obtained, that this display produces the best performance.

d. Experiment V--Variable-Location Ripple Tracking

(1) Design

To investigate the effect of presenting the tactile information of the ripple display on different bodily areas and with different spatial arrangements, several tracking tests were conducted. The same command signal and integrating vehicle of Experiment I were used with the 0.89-volt full-scale ripple display recommended by Experiment IV. The experiments were conducted on four different body areas: one fingertip, several fingers, the back of the hand, and the forearm. In addition, some of the tests involved nonuniform stimulus spacings. The five tracking runs engaged in by two subjects are illustrated schematically in Fig. 10.

(2) Results

The normalized error power obtained from the tracking runs is shown in Table IX. An entry consisting of two numbers indicates that two tracking runs were made in that condition. An analysis of variance of the different-location error scores showed them to be significantly different [$F(4,5) = 19.8$, $p < 0.005$]. The five-percent t-value for comparing pairs of average data points is 0.089. When this value is used, the performance of the five runs can be ranked from lower to higher error scores as follows: a, b, e < c < d.

Table IX

NORMALIZED ERROR-POWER SCORES IN THE VARIABLE-LOCATION EXPERIMENT

Location	Subject JH	Subject KE	Average
(a) Back of hand	0.29	0.34	0.315
(b) Palmar side of fingers	0.27, 0.42	0.31, 0.42	0.355
(c) Fingertip-expanded scale	0.88, 0.26	0.60, 0.58	0.53
(d) Forearm-equal spacing	0.62	0.64	0.63
(e) Forearm-expanded scale	0.28	0.34	0.31

The uniformly spaced array on the back of the hand was better than the uniform array on the forearm. This is probably due to the anatomical reference (or zero reference) furnished by the knuckle of the hand. Increasing the spacing of the stimulators on the forearm as shown in Fig. 10(e) reduced the subjects' error power by about two to one.

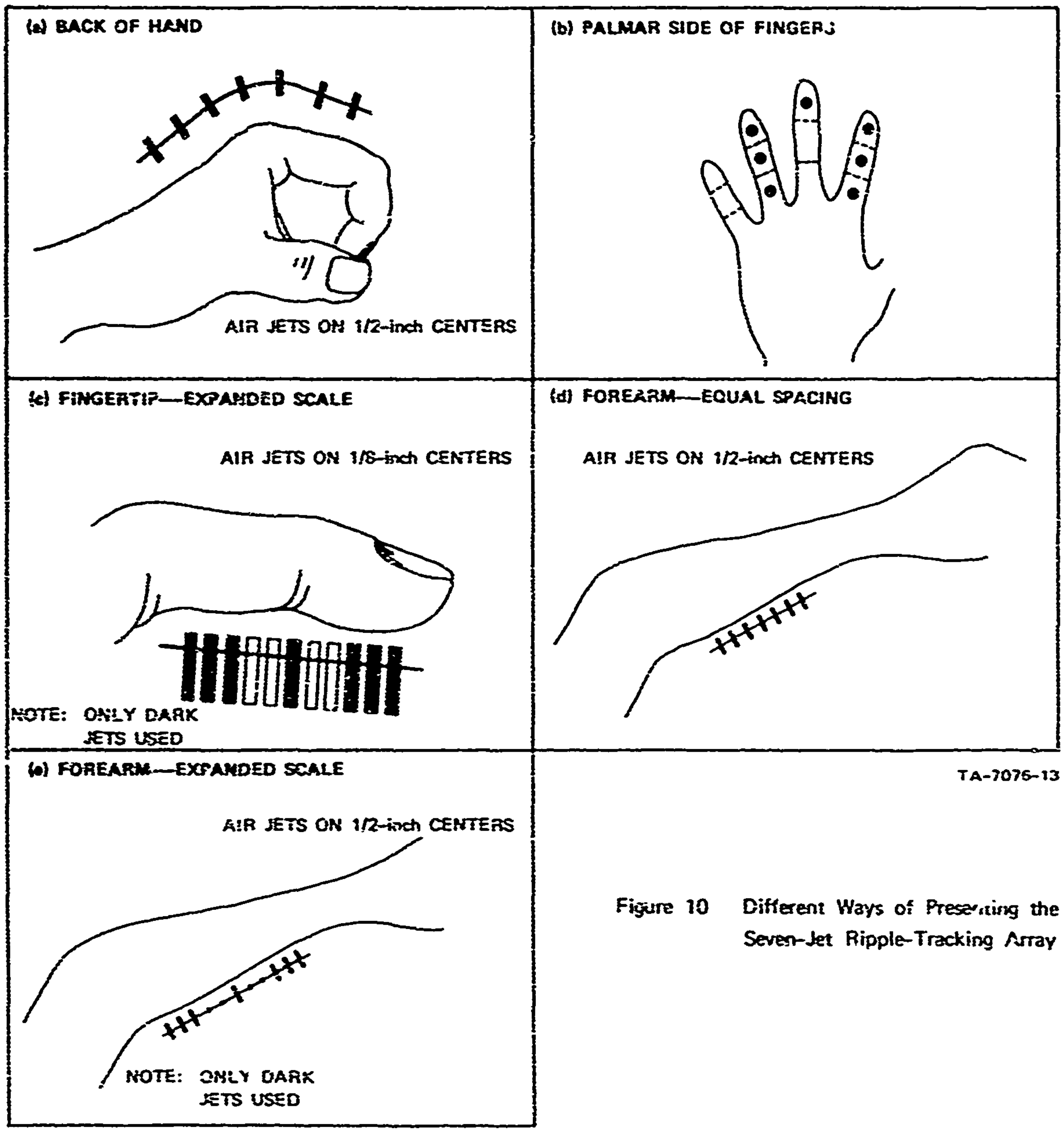

Figure 10 Different Ways of Presenting the Seven-Jet Ripple-Tracking Array

This added spacing serves to make the two error directions more distinquishable, as an anatomical landmark does. This effect was also found on the fingertip although formal tests were not run with uniform jet spacing because the interpretation of the display was so difficult. One interesting aspect of the expanded scale displays is that they approximate the two-vibrator linear-display described in Experiment I when the spacing is large. The same is true of the finger display (c) because under the conditions in which good tracking performance was obtained, only the first jets either side of zero came on.

The main results of the experiment are that similar good tracking performance can be obtained on three different areas: the back of the hand, the palmar side of the fingers, and the forearm. The describing functions for these last three areas were obtained for both test subjects. Since the differences between these areas were not significant, the test runs were averaged together and plotted in Fig. 11. Fitting the crossover model to the data gives an equivalent operator time delay of 0.16 s and an equivalent operator gain of 3.7.

3. COMPARISON OF TACTILE DISPLAYS

Considering the vibrator and air-jet tactile displays tested in this section, the best are: (1) the linear, differential, and threshold-intensity algorithms using two vibrators with full-scale display occurring at about 50 to 100 percent of the command signal RMS value, (2) the air-jet ripple-tracking display with the highest ripple rate when full-scale display occurred at 100 to 150 percent of the command signal RMS value. To compare these tactile displays with typical visual-display performance, the equivalent gain, K_e, and equivalent time-delay parameters for the displays were computed and shown in Table X. Also shown in the table are the same parameters computed from data of Bliss (1967) who used two continuous-position tactile displays. Because the other investigators listed in Table I failed to use describing-function analyses, none of their results could be included in the comparison.

Since the displays tested in this report used an integrating vehicle and those of Bliss (1967) a position vehicle, the comparison will be made in two parts. The equivalent-gain and time-delay parameters for the integrating vehicle displays have been plotted in Fig. 12. Equivalent parameters from McRuer et al. (1965, p. 153) obtained from visual compensatory tracking runs using the same integrating vehicle and several test subjects is also included as a reference. It can be seen in Fig. 12 that the air-jet ripple-tracking display comes closer to the visual characteristics than do the others. The vibrator displays yield less gain and greater time delays than the ripple display. The ripple display offers performance fairly comparable to that obtained with a standard visual display. The gain is 20 percent less but the equivalent time delay is 12 percent shorter.

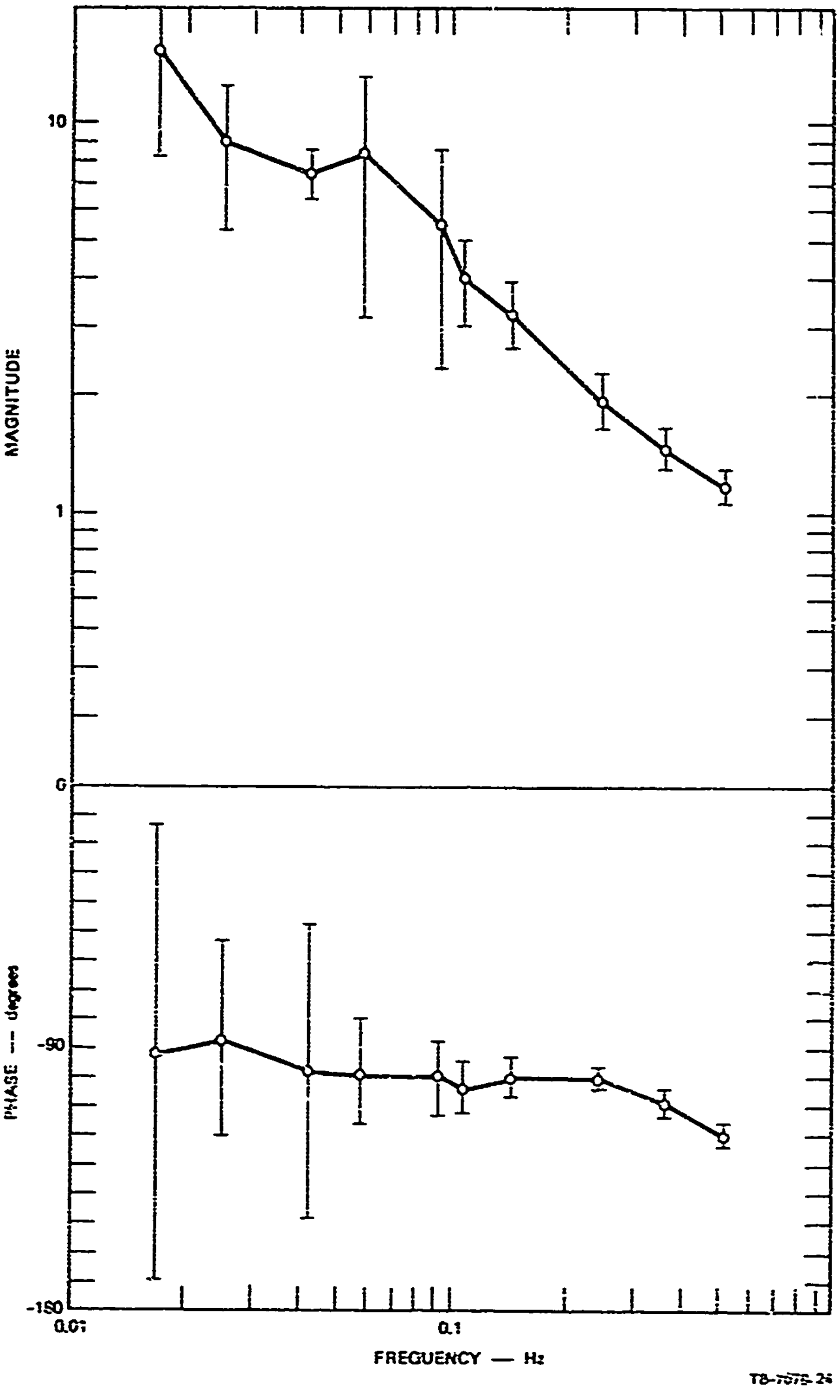

Figure 11 Combined Operator/Integrating-Vehicle Describing Functions for the Best Ripple-Tracking Display on the Better Body Areas (averaged data for three subjects). The length of the tolerance bars is two standard deviations.

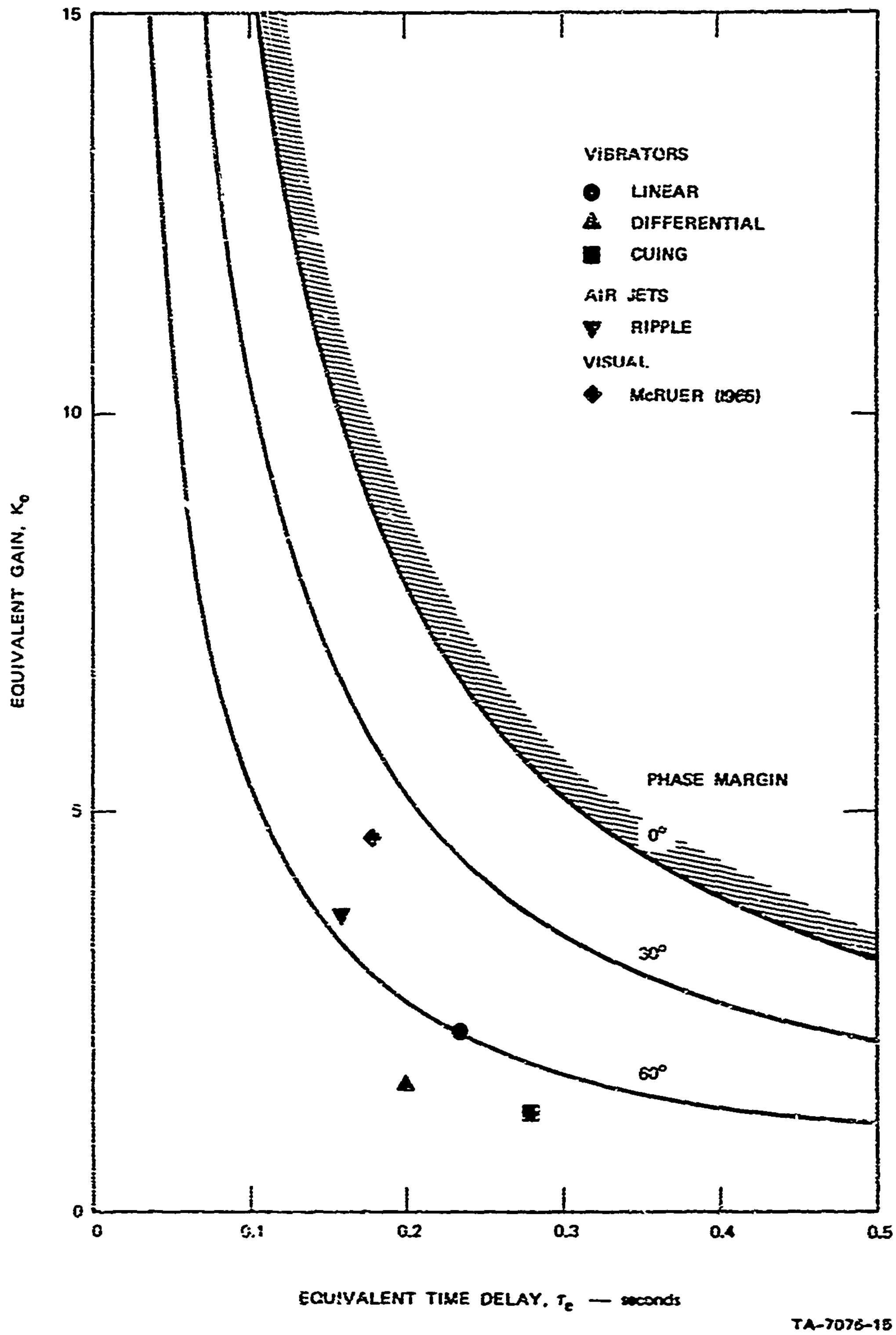

Figure 12 Stability Plot Comparing the Tactile Data with Previous Visual Data, All of Which Were Obtained with an Integrating Vehicle

Table X

EQUIVALENT GAIN AND TIME-DELAY PARAMETERS FOR THE SIMPLE CROSSOVER MODEL CALCULATED FOR SEVERAL DISPLAYS

Display	K_e	τ_e
Vibrator Displays		
Linear	2.24	0.24
Differential	1.56	0.20
Threshold	1.19	0.28
Ripple Display	3.7	0.16
Position Display Bliss (1967)		
Air Jet	3.4	0.85
Contact	6.5	0.37

These same two parameters (K_e and τ_e) are plotted in Fig. 13 for the visual and tactile displays using the position vehicle. Again, the similar results of McRuer (1965, p. 93) and Elkind (1956, R-40 and B-6 command signals) are included as references using a visual display and a position vehicle. The results of Bliss (1967) using a visual display and two types of tactile displays have been fitted with the crossover-model parameters and these are also shown in the figure. As Bliss' visual and tactile contact data was obtained from one subject, some care must be exercised in interpreting it. As the subject was quite good, his visual gain being much higher than McRuer and Elkind's average data, the gains on both his tactile and visual runs should be scaled down by about 30 percent to match that of the average subject. If this were done the subject's gain would be about four, and quite comparable to that obtained with the ripple display using the integrating vehicle. The other display represented in Fig. 13 is the continuously movable air-jet display. This point, representing the average of three subjects' scores, shows that fair gain but very large time delays were obtained with this display.

Comparing all of the displays in Figs. 12 and 13 shows that the ripple and continuous-contact displays are the best, and vibrator displays intermediate. The moving-jet display should not be used in pilot cuing because of the inordinately long time delay associated with it. As far as usable body areas are concerned, (1) the vibrator display was equally effective on all areas tested, (2) the ripple display was most effective on only three areas and, (3) the continuous-contact display of Bliss (1967), though effective, was tested only on one area, the palmar surface of the hand. For tactile displays for pilot cuing, we recommend both the vibrator and ripple displays over the other.

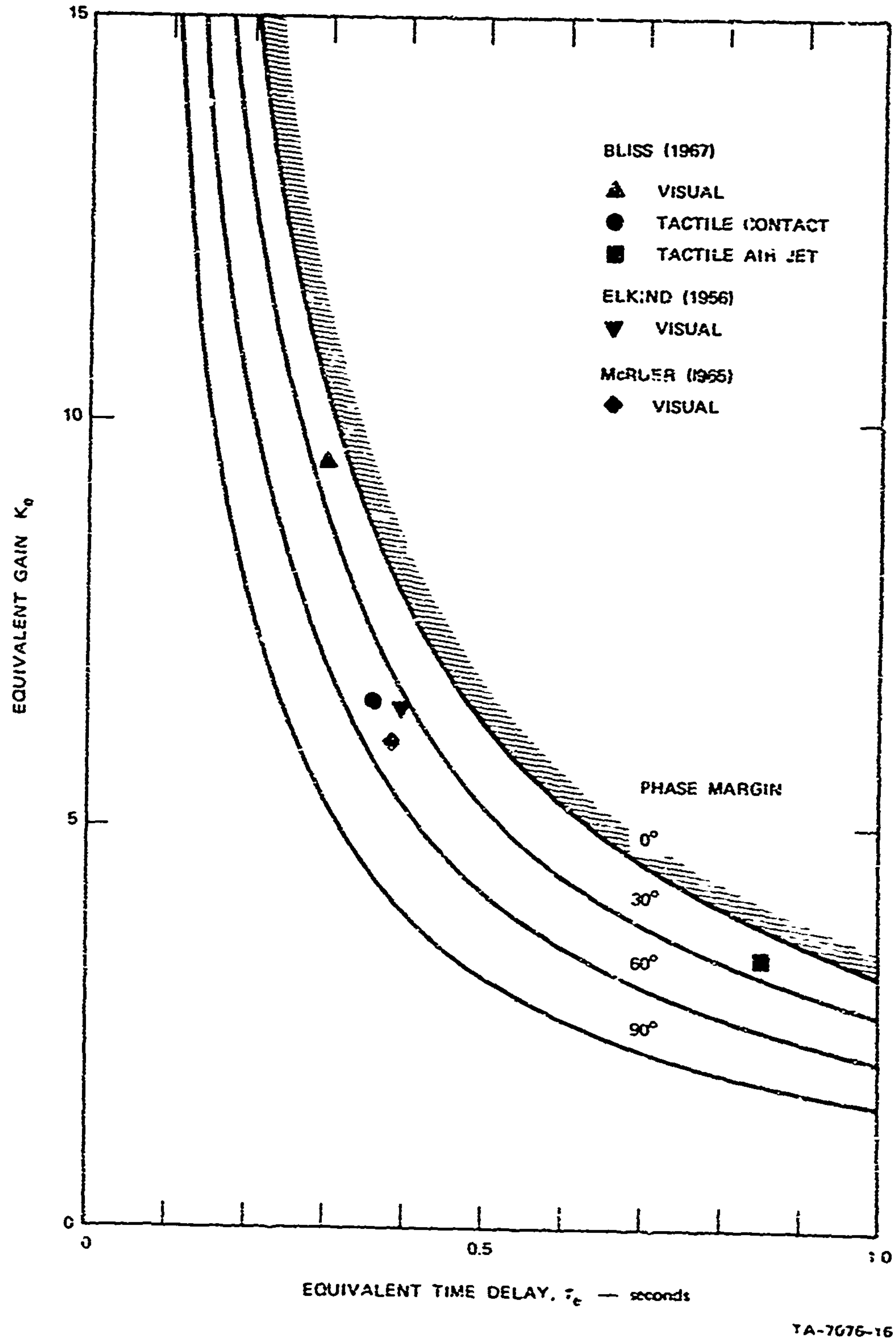

Figure 13 Stability Plot Comparing Tactile Data with Previous Visual Data, All of Which Were Obtained with a Position Vehicle

SECTION V

DISPLAY-EVALUATION EXPERIMENTS IN A GAT-1 TRAINER

1. INTRODUCTION

As a result of the work described in Sec. II, three experiments were designed using reference signals available from a GAT-1 trainer. The first experiment described in this section compares five tactile displays chosen on the basis of the preliminary experiments discussed in the previous section, in an altitude-holding task. The second experiment compares performance with and without tactile cuing in an altitude-tracking task, and the third compares ILS landing approaches with and without tactile cuing.

An experimental design including all three experiments was constructed that provided the following properties:

(1) Compares flight performance with and without cuing on all three of the experiments

(2) Compares tactile cuing in two air-turbulence conditions (rough and smooth air)

(3) Was balanced against learning effects.

The results of the design are presented experiment-by-experiment in the following sections. In all of the experiments, subject's error-power scores were obtained after the test runs and used to compare the resulting changes in performance. In addition, a plot of the instantaneous flight variables important to the experiment was made on an X-Y recorder so that the state of the individual pilot could be monitored during the run. These plots were valuable not only for understanding the results but for explaining to the pilots what was being monitored and how they were improving. In addition, pilot describing functions were used to compare performance during the tracking tests.

2. ADDITIONS TO THE GAT-1 TRAINER

The GAT-1* trainer was used in all of the flight-simulation experiments described in this report. A patch panel (shown in Fig. 14) was added to the side of the trainer for making connections between the tactile displays inside and the display-driving equipment outside. The patch panel also allowed connections between the LINC-8 computer and electrical test points within the GAT-1.

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*The GAT-1 is a fully instrumented ground-base trainer manufactured by General Precision, Inc. It is designed to have handling characteristics similar to those of the Cessna 150.

Figure 14 GAT-1 Trainer with Patch Panel for Connections to the Computer. From left to right are the plotting table, display generator rack, experiment-controlling teletype with operator, and GAT-1.

For monitoring and injecting signals to the GAT-1, two interface circuits were designed. One circuit for altitude and heading experiments monitored both true altitude and heading, and allowed a command signal from the LINC-8 computer to be realistically added to the GAT-1's internal altitude. Another interface circuit allowed the computer to monitor both glide slope and airspeed while making an ILS approach. The detailed circuit drawings for these two interfaces are given in Appendix A.

In order to attach displays to the control yoke, a mocked-up yoke was made, preserving the dimensions of the original. This wooden yoke is shown in Fig. 15 as it was used in the experiments. In total, three different displays were mounted on it in different parts of the experiment.

3. TACTILE DISPLAYS

Five tactile displays were chosen for use in the flight-simulation experiments conducted in the GAT-1 trainer. These included the air-jet ripple-tracking display and two of the vibrator displays evaluated on manual control tasks in Sec. IV. In addition, two button displays mounted in the control stick were used that were not given previous testing. The five displays are described below:

(1) Air-Jet Ripple Display. This display, described in Sec. IV, cycles at the high 60-Hz rate. Figure 16 shows the jets mounted on the control yoke of the GAT-1. The air-jet valves are controlled directly by the LINC-8 monitor program.

(2) Two-Vibrator Threshold Cuing Display. The two vibrators for this display have been described in Sec. IV and are shown in Fig. 17 as used for altitude cuing. When used to convey heading information, the vibrators are placed on the left and right upper arms. When the error level is acceptable, neither vibrator is on; when too large in a given direction, one of the vibrators comes on at full strength.

(3) Two-Vibrator Linear Display. The vibrators are mounted the same as for cuing above; however, the presentation algorithm is linear as shown in Fig. 2(a). With larger errors, the vibration strength of the appropriate vibrator becomes larger.

(4) Palm-Button Display. A two-ended plunger moves through the body of the left control handle as illustrated in Fig. 18. With zero error the button is in the neutral position flush with both front- and back-handle surfaces. With either positive or negative error, the plunger is driven by a servo motor a proportional distance out of the handle. For altitude control, the plunger motion was front-to-back and for heading control it was rotated 90° so that motion was left-to-right.

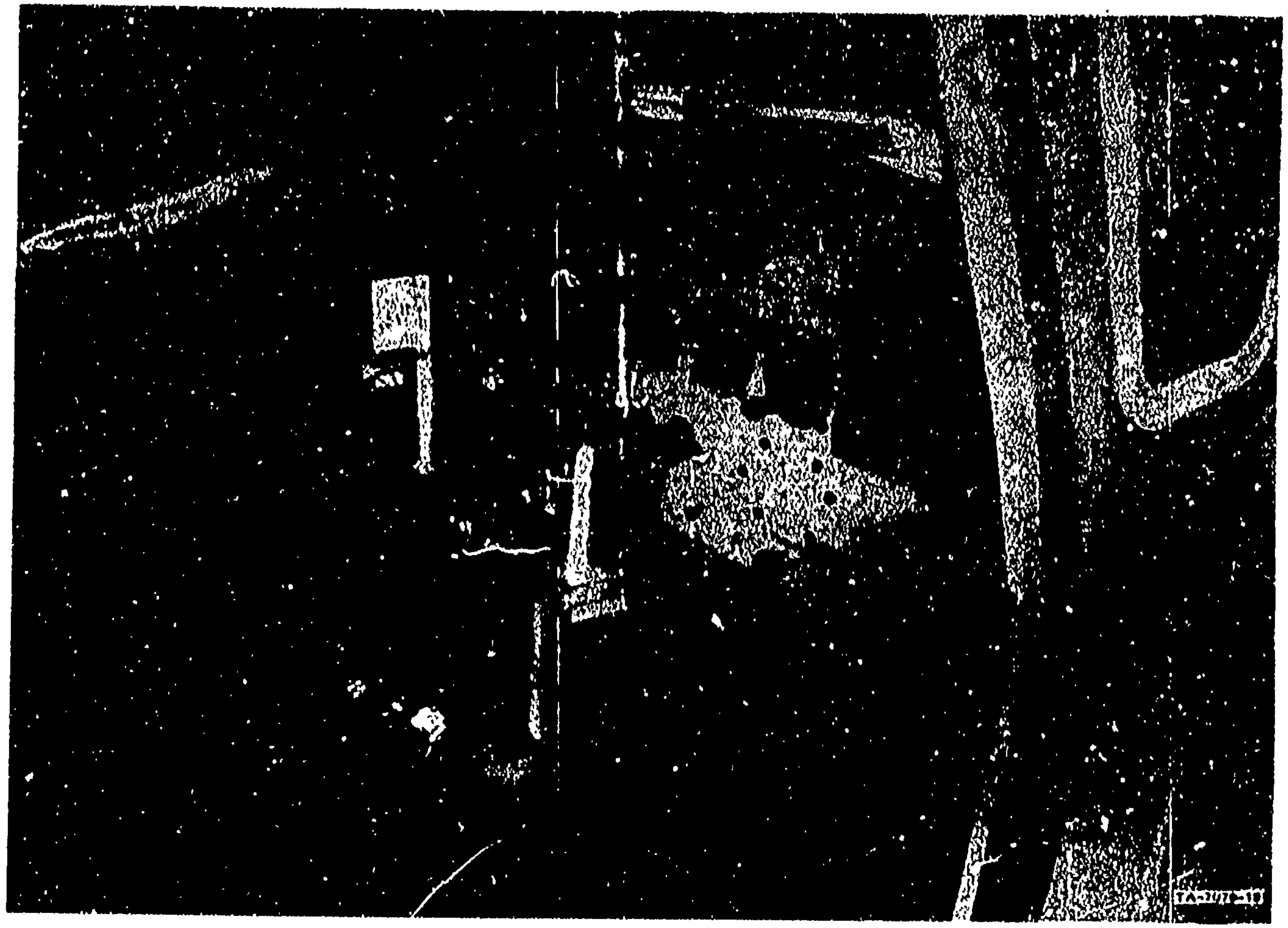


Figure 15 Interior of GAT-1 Cockpit Showing the Mocked-up Yoke with a Tactile Display on Each Handle (for illustrative purposes only). Note the position servomotor used to drive button displays in lower left-hand corner of picture.

Figure 16 Air-Jet Ripple-Tracking Display Mounted on Handle of Mock-up Control Yoke. The seven jets on an adjustable metal strap are driven by electromechanical valves under the yoke.

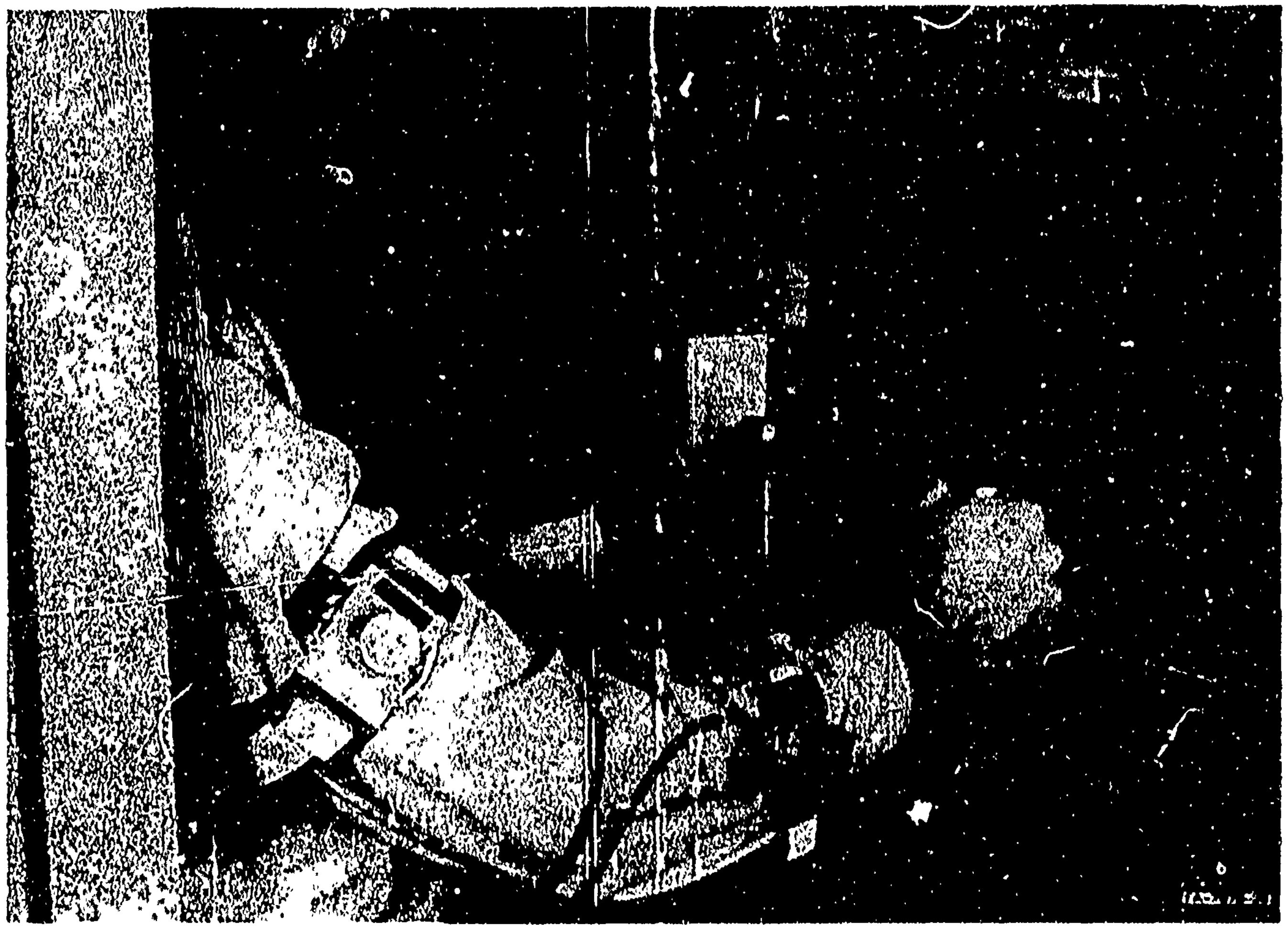


Figure 17 Two Vibrators for Cuing and Linear Display Mounted on Right Arm of Pilot as in Altitude-Holding Experiments. The vibrators are driven by the display generator outside the GAT-1.

Figure 18 Palm-Button Display Mounted in One Handle of the Mocked-up Yoke. The buttons, driven through a flexible push rod by a servomotor, push against either the palm or the fingers.

(5) Thumb-Button Display. This display, shown in Fig. 19, is similar to the palm-button display above. Here, two buttons move alternately in and out of the top of the handle. With zero error the buttons are both flush, and with positive or negative error one button or the other is driven up out of the handle. For altitude control the buttons were aligned from front-to-back, while for heading control they were left-to-right.

4. EXPERIMENT CAH--HOLDING CONSTANT ALTITUDE AND HEADING

a. Design

The five different tactile displays were compared on a task requiring pilots to hold a constant altitude (1000 ft) and heading (270°) while alternately changing their airspeed between two limits (80 and 110 mph) every 90 seconds. During each five-minute experimental run the pilots' altitude and heading deviations from the required constant values were sampled by the computer. After each run the computer printed out the error powers of each deviation on the control teletype. The conditions under which the experiment are carried out are more completely described in Appendix B.

Three private pilots with different amounts of training were selected for the experiment. The three, who had not yet qualified for their instrument license, were graduate students at Stanford University and were paid hourly for their time in the experiment. Their initials and flight hours as of the beginning of the experiment are listed below:

Pilot BD--70 hours
Pilot CR--150 hours
Pilot TH--430 hours.

To test each display, four five-minute test runs were conducted. Two runs were made using one tactile display in addition to the standard instruments, and two runs were made using the instruments only. Each of these pairs of tests was further subdivided into a run with maximum rough air as simulated by the GAT-1 electronic system, and a run with no rough air (smooth air). The four test runs were always consecutive, with both the first and last run of the series being the control (or no display) condition. Either the first two or last two runs of the series (selected at random) included the rough-air condition. Thus, the four-test series was balanced to reduce the practice effect on the experimental results. The two main experimental variables are display type, and amount of turbulence. The measure of performance is the change in error power between the similar-display and no-display condition.

Figure 19 Thumb-Button Display Mounted on Control Handle. The small buttons move teeter-totter fashion against the thumb. Note push rod to servo driver.

b. Results from Altitude Cuing

The altitude and heading error-power scores from the matched pairs of runs with and without the tactile display were converted to logarithmic units for comparison. The logarithmic scale is the only one that gives equal and opposite scores to an increase and decrease in error power by any given factor. When base ten logarithms are used, logarithmic error-power changes of plus one and minus one, respectively, indicate error-power increases and decreases by a factor of 10. The resulting error-power changes measured by subtracting the log error power without display from the log error power with display are shown in Table XI. Negative entries in the table mean that the use of the display resulted in reduced error power, and positive entries mean that its use resulted in increased error power.

Table XI

AC ERROR-POWER CHANGES, IN LOG UNITS, FOR THE FIVE DISPLAYS TESTED

Display	Altitude		Heading	
	Smooth Air	Rough Air	Smooth Air	Rough Air
Air-Jet Ripple	-0.26 -0.31 -1.00	-0.08 +0.06 +0.05	+0.22 -0.45 -0.34	-0.03 -0.14 +0.41
Cuing Vibrator	-0.28 -0.10	+0.23 -0.19	-0.04 -0.19	-0.29 -0.21
Linear Vibrator	+0.54 -0.17	+0.06 +0.01	+0.45 -0.05	-0.25 0.00
Thumb Button	-0.15 +0.02	+0.38 -0.15 -0.33	-0.06 +0.14	+0.23 -0.09 -0.14
Palm Button	+0.07 -0.09	-0.01 +0.09	+0.15 +0.15	-0.02 -0.31
Average Change	-0.157*	+0.008	+0.041	-0.069
t value (df = 26)	-1.722	+0.100	+0.447	-0.771

*Significant at the 5 percent level.

The average changes produced by the additional tactile displays have been calculated and are shown at the bottom of Table XI along with the one-sided t-test for differences from zero. In only one case was

there a significant reduction in error power. This was in the altitude error power in the absence of rough air. Here, the decrease of 0.157 log unit represents a 30-percent decrease in altitude error power. Since the same change in the rough-air condition is very small, we must assume that the smooth-air condition is more favorable to the tactile displays. When asked about the difference between the rough- and smooth-air conditions when using the tactile displays, the pilots generally commented that they paid more attention to the tactile displays in the smooth-air condition.

The same error-power changes were averaged over air-turbulence conditions to find the error-power changes produced by the five displays. The average error-power changes for each tactile display are shown in Table XII and were tested for significance using t-tests. Only one display, the air-jet ripple-tracking display produced a significant change. Here the change was a decrease in error power of 0.285 log unit or 48 percent.

Table XII

ERROR-POWER CHANGES, IN LOG UNITS

AVERAGED OVER PILOTS AND ROUGH-AIR CONDITION

Display	Altitude Change	Heading Change
Air-Jet Ripple	-0.258*	-0.055
Cuing Vibrator	-0.086	-0.181
Linear Vibrator	+0.110	+0.036
Thumb Button	-0.047	+0.018
Palm Button	+0.015	+0.061

*Significant at the 2.5-percent level.

Since this particular experiment was not very sensitive in determining differences with and without the tactile cuing devices, a simple questionnaire was prepared asking the pilots to rank the five displays from best to worst and to give a comment on each display. Surprisingly, the pilots found the choice easy to make (i.e., there were large subjective differences between the best and worst devices) and indicated with their comments that they were very positive that their favorite displays were helpful to them and that some displays were very burdensome or confusing.

While it was originally intended to average the rankings and test them statistically, this approach was abandoned. It turned out that while most pilots thought the air jets were intermediate in value, two

enthusiastically rated the vibrators attached to the body as best; while one, with equal enthusiasm, rated the thumb buttons best. Since the pilots spent considerable time preparing their comments and since their opinions are considered valuable, the three questionnaires are presented in unabridged form in Appendic C.

The pilot questionnaires show a range of individual preferences in tactile displays. While two pilots preferred to be warned by the automatic body vibrators when they were in error (interestingly, the pilots with less flight time) and preferred not to use the stick-mounted display requiring their effort, one pilot (with the greatest flight time) subscribed emphatically to the opposite view. In the design of a pilot cuing system these individual differences may have to be taken into consideration.

In order to determine whether change in performance using the displays was correlated with pilot experience, the average change in error power over all runs of each pilot was computed. In order of increasing experience, pilots BD, CR, and TH showed changes of -21, -25, and +7 percent, respectively, indicating that the pilots with the least experience improved more than the pilot with the most experience.

c. Results from Heading Cuing

To find the effect of cuing on a secondary or more slowly varying task, each pilot's favorite display was used to give heading deviations from the required course. The resulting error-power changes are shown in Table XIII. The average results for each combined air-turbulence and coordinate condition were calculated and are shown in the

Table XIII

ERROR-POWER CHANGES, IN LOG UNITS, FOR THE HEADING CUING CASES

Pilot	Display	Altitude		Heading	
		Smooth Air	Rough Air	Smooth Air	Rough Air
TH	Thumb Button	+0.23	-0.30	-0.50	+0.19
BD	Cuing Vibrator	+0.34	+0.23	-0.27	-1.22
CR	Cuing Vibrator	-0.22	-0.13	-0.10	-0.24
Pilot Average		+0.119	-0.068	-0.293	-0.422
Coordinate Average		+0.025		-0.358*	

*Significant at the 5-percent level.

table. These averages were tested with t-tests and it was found that only the heading error power changed significantly. The change of -0.358 log unit represents an average error-power drop of 56 percent. Comparing these heading cuing results with the previous altitude cuing results indicates that cuing on a given flight variable reduces the error in that variable only.

The pilot most influenced by the cuing system was the one with the least experience. He was also the one with the consistently largest error scores and thus the one with the most room for improvement. To further illustrate the changes brought about by cuing, the plot of pilot BD's flight deviations for the heading cuing experiment is shown in Fig. 20. The figure shows instantaneous altitude and heading deviations for four consecutive five-minute test runs. Run 3 illustrates the typical deviations of this subject over the five-minute run without cuing--fair control over altitude and poor control over heading. With the addition of heading cuing in the next run (Run 4), better heading deviations but worse altitude deviations were obtained. In Run 5 both deviations improve even with the additional influence of rough air, and in Run 6, even after cuing had ceased, altitude deviations were reduced to those of Run 3 but heading deviations were more than halved. Interestingly, this subject did not immediately revert to his pre-cuing deviations when cuing was removed but continued better performance for awhile. The next test sessions several days later showed that he had reverted to his original performance pattern (shown in Run 3) of neglecting heading information. The fact that the subject had learned something temporarily and retained it even after direct reinforcement was removed indicates that this cuing method shows promise in teaching. One other pilot (CR) with intermediate experience reacted to the cuing similarly, but to a lesser degree. Apparently pilots with less experience learn more or change their instrument scans and priorities more than pilots with more experience.

5. EXPERIMENT AT--ALTITUDE TRACKING

a. Design

This experiment is very similar to the previous experiment in that the same subjects participated in it and the same air-turbulence conditions were used. Tests were of the same five-minute duration balanced for turbulence and learning changes. The display used by each pilot was the one that he preferred, as previously discussed. The task in this experiment was the same as in Experiment CAH (to hold constant altitude at 1000 feet and constant heading at 270°) except that a sum-of-sinusoids command signal was added to the GAT-1 altimeter both to make the task fairly difficult and to measure pilot describing functions with and without tactile cuing in addition to the usual aircraft instruments. The spectrum of the command signal is given in Table XIV. The signal was tailored to have low-frequency components approximating rough-air turbulence within the controlling ability of the GAT-1 trainer--i.e., the

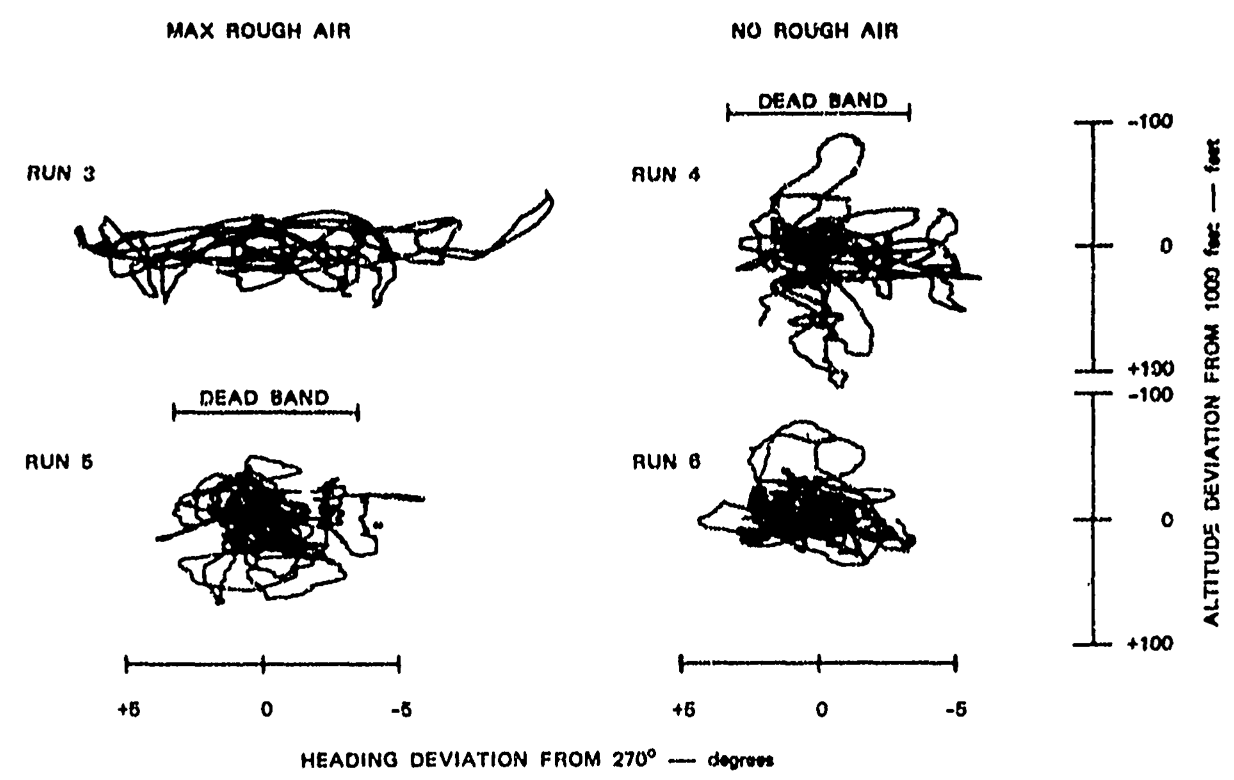


Figure 20 Calibrated Flight Deviations for Subject BD. Runs 3 and 5 are with rough air on and runs 4 and 6 with it off. Cuing was applied with the cuing vibrators which were off in the heading dead bands shown and full on outside of these bands.

Table XIV

COMMAND-SIGNAL COMPONENTS

FOR GAT-1 ALTITUDE TRACKING

Component	Amplitude	Frequency (Hz)
1	6	0.0042
2	6	0.0083
3	6	0.0125
4	5	0.021
5	5	0.029
6	4	0.050
7	2	0.075
8	1	0.100
9	1	0.129
10	1	0.196

rate of climb and descent was never so large that the airplane could not mechanically track it. The maximum altitude deviation from 1000 feet during the entire run was about 350 feet. More details of the experiment are given in Appendix B.

b. Results

The altitude and heading-error scores with the tactile displays were converted to logarithmic units and subtracted from the similar air-turbulence control condition, as done in the previous experiment. These data are presented in Table XV for comparison. Again, negative scores indicate the reduction in error power using the tactile display, while positive scores indicate an increase. As none of the averages in Table XV were large enough to be significant, there is insufficient information to show that either altitude cuing, heading cuing, or air-turbulence condition affected the results. This is somewhat in accord with the results of the previous experiment, where it was noted that the tactile displays caused a significant error reduction with the smooth-air condition but not with rough air. Taken together with the negative results of this experiment, which required much more pilot activity to control the simulator than in the moderate "rough-air" condition of the previous experiment, the results of the two experiments show that the effectiveness of the tactile displays may be inversely related to pilot activity.

Table XV

ERROR-POWER CHANGES, IN LOG UNITS, FOR HEADING AND ALTITUDE CUING DURING ALTITUDE TRACKING

	Altitude		Heading	
	Smooth Air	Rough Air	Smooth Air	Rough Air
Altitude Cuing Scores	0.164 -0.044	0.124 0.044 0.000	0.184 0.240	0.084 -0.480 0.300
Average	0.058		0.066	
Heading Cuing Scores	0.032 -0.028	0.000 0.080 0.000	-0.076 -0.112	0.272 -0.060 0.020
Average	0.017		0.008	
Turbulence Average	0.031	0.043	0.059	0.029

In an effort to compare cuing and no cuing results with better sensitivity, combined GAT-1/pilot describing functions for altitude control were obtained for runs with both heading and altitude cuing. The available describing functions for each condition were averaged over turbulence condition and pilots, and are plotted in Figs. 21 and 22. The curves of both the figures show very little difference between the cuing and no-cuing conditions. This is added evidence that the tactile cues were neglected in favor of the primary visual instruments in this rather difficult tracking task.

6. EXPERIMENT CS—CONSTANT-SPEED ILS LANDING APPROACH

a. Design

In form, this experiment is very similar to Experiment CAH, as was the previous experiment. Again the same three subjects, same counterbalanced turbulence conditions, and five-minute test-run length were used. The task in this case is different, however. After taking off and flying to 2000 feet, the pilot was positioned about ten miles from the end of the runway and within a mile of the ILS beacon. He was instructed to fly to the center of the beacon and fly down it, on center, at 85 mph. Since the pilots knew the beacon heading was 288°, a side wind of random direction and strength, both of which were unknown to them, was added to make repetitions of the task different and require some active reasoning to follow the beam. The pilot flew to the beam's left-right center first and then flew at a constant 2000-foot altitude until he arrived at the glide-slope

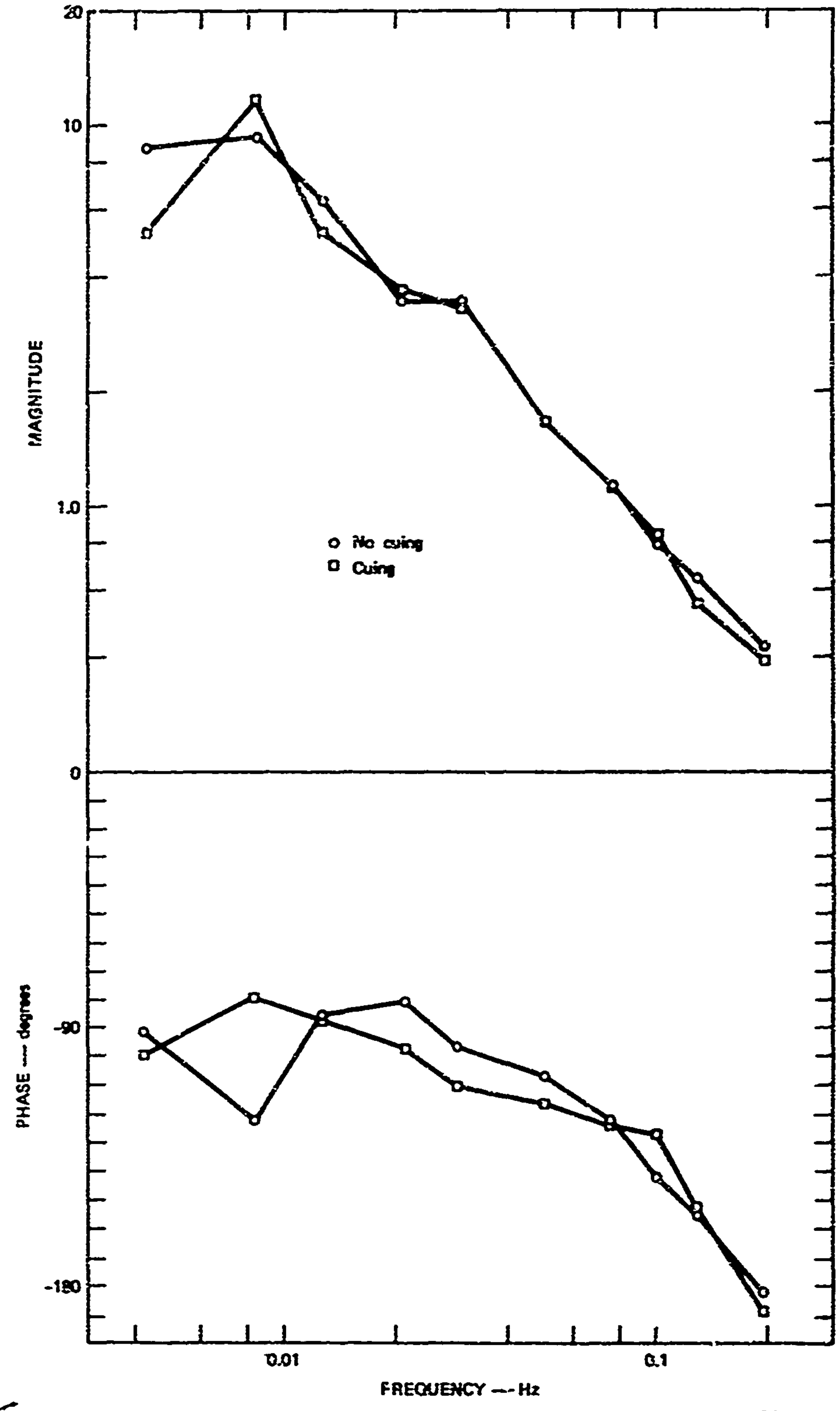


Figure 21 Combined Pilot/Vehicle Describing Functions Obtained with and Without Altitude Cuing in Addition to the Standard Instruments

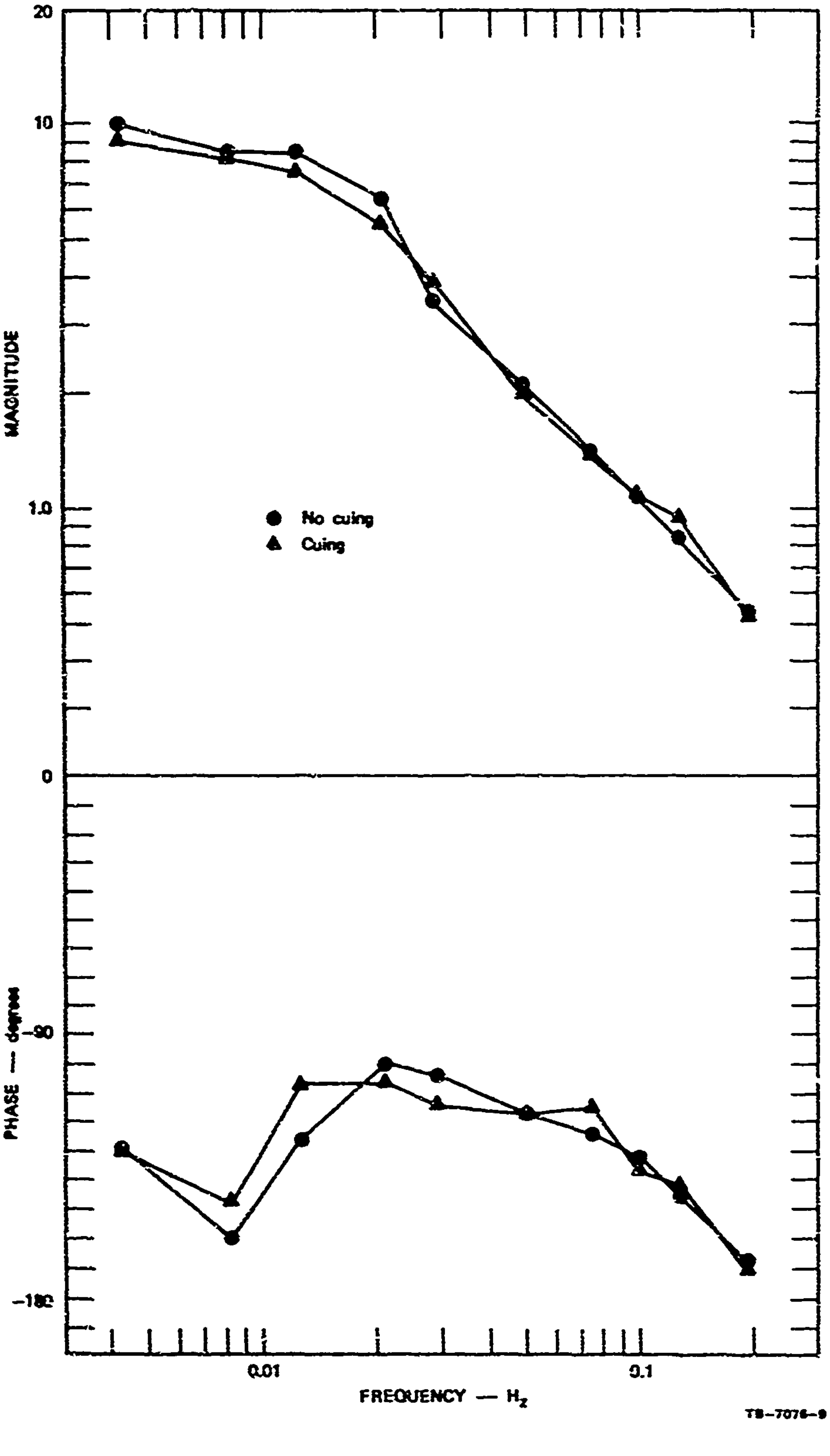


Figure 22 Combined Pilot/Vehicle Describing Functions Obtained with and Without Heading Cuing in Addition to the Standard Flight Instruments

beam. He then started his approach and the five-minute monitoring program was turned on. He proceeded down the beam for five minutes while the error power in both his glide-slope deviations from zero, and airspeed deviations from 85 mph, were accumulated by the computer. This five-minute run took the pilot approximately to the middle marker at an altitude of 300 feet. At this point the pilot was instructed to climb back to 2000 feet and get ready for the next run.

In addition to the airspeed indicator a simple cuing display with vibrators on the upper and lower left arm was used when required by the experimental design. Both vibrators were off when the airspeed was within 5 mph of 85 mph, but the upper-arm vibrator came full on when the airspeed was 5 mph too slow and the lower-arm vibrator came full on when 5 mph too fast. These two locations were chosen by the pilots themselves to be the clearest to interpret. Other details of this experiment are given in Appendix B.

b. Results

As with the previous two experiments the error power in the deviations of airspeed from 85 mph and in the glide slope from zero were converted to logarithmic units. Then the control (noncuing) test error scores were subtracted from the matching cuing test error scores to determine the logarithm of the change. These power changes for both turbulence conditions and both instruments monitored are given in Table XVI.

Table XVI

ERROR-POWER CHANGES, IN LOG UNITS, FOR TACTILE CUING DURING ILS LANDING APPROACHES

Pilot	Airspeed		Glide Slope	
	Smooth Air	Rough Air	Smooth Air	Rough Air
BD	0.124	−0.201	0.087	0.356
BD	0.024	−0.242	−0.019	0.085
TH	−0.078	−0.157	−0.330	0.277
TH	−0.256	0.159	−0.018	0.087
CR	−0.073	0.083	−0.531	−0.182
Pilot Average	−0.052	−0.072	−0.162	0.125
Coordinate Average	−0.062		−0.019	

Pilots BD and TH completed the four test series twice, while CR only completed it once. The changes in error power shown in Table XVI appear to be spontaneous and variable. There is no column that is composed entirely of numbers of the same sign. Indeed, when the pilot and coordinate averages were tested for significance with t-tests, none of the averages were significantly different from zero. We must assume that the changes in performance brought about by the tactile cues were small or irregular.

The pilots evidently could adequately scan the airspeed and ILS instruments and did not use the tactile cues in controlling the aircraft. In order to test this interpretation, pilot BD, on his second day of ILS approaches (eight having been completed, four with tactile cuing) was given a four-test series in which the airspeed instrument was covered up when the tactile airspeed cues were used. In smooth- and rough-air conditions his airspeed error-power scores with tactile cuing only were, respectively, 14.3 and 1.98 times larger than his control scores with the visual instruments only! The large (14.3) error score occurred on the first tactile-only run and resulted from misinterpreting the direction of the cues early in the experiment. It was obvious from this short test that one pilot at least was not using the directional nature of the cues. Special training with tactile cuing only (no parallel instrument) should have been given before testing was started to make certain the pilots were familiar with the cues.

In order to see how the cues would affect performance when they provided glide-slope deviations instead of airspeed deviations one auxiliary, four-test series was run using pilot TH on his second day of ILS landing approaches. Although the cuing runs produced glide-slope error-power scores 62 percent (rough air) and 25 percent (smooth air) lower than the control runs, these improvements were not judged to be significant.

One of the key reasons that the ILS landing is a difficult task is that pilots must look at instruments inside the plane as well as the runway and air traffic outside the plane while making their approach. This inside and outside viewing, which is an important problem in landing, could not be simulated on the GAT-1 trainer. As a result, pilots spent their full time monitoring their instruments and did a good job without unreasonable stress. If the outside part of landing could have been simulated, we feel that the tactile cuing system would have had a more natural position in helping the pilot determine what his instruments were telling him while he was looking out the window.

SECTION VI

REDUCED-SCALE TEST OF A TACTILE CUING SYSTEM

Considering the results of the preliminary experiments described in Sec. V along with the questionnaires and other comments furnished by the pilots, an experiment was designed to more effectively measure the changes brought about by tactile cuing. This more sensitive experiment measured the amount of time a pilot has to handle other work loads with and without cuing, and his rate of learning with and without cuing. Since improvement with practice on these tasks is standard, two balanced groups of subjects were needed to make these comparisons possible. One group received the extra cuing signals and the other, the control group, did not. Changes brought about by cuing were measured by statistically comparing the two groups using the intrapilot variances as the base. The main task in the experiment was two-dimensional holding (altitude and heading) with a moderate-amplitude, low-bandwidth noise added to each dimension. In the experiment, learning rate was measured by measuring performance on several repetitions of the same task, each spaced a few days apart. Extra work load in the experiment was achieved by giving the pilot additional information to process while performing this standard flying task. The particular loads used in the experiment were (1) presenting the pilots with a simple list of mathematics problems to perform, and (2) requiring pilots to take and repeat typical clearance messages. An additional unloaded test was made to establish a performance baseline for comparing changes with additional work load.

Although the present experiment used only two pilots in each group and included only five tests spaced over three weeks, it should be considered a small-scale, short-timespan version of a more comprehensive test to be conducted by the Air Force using a larger number of subjects and being conducted over a greater length of time.

1. DESIGN

a. Apparatus

The experiment was conducted with the GAT-1 trainer-computer system previously described and shown in Fig. 14. External vision was obscured using the fogged windows provided with the GAT-1, so that the tests involved purely instrument flying. The tactile cuing system consisted of two vibrators mounted on the left and right upper arms, driven with the threshold algorithm shown in Fig. 2(c). The gain of the cuing system was adjusted so that the appropriate vibrator came full on when the heading error was greater than 5.7 degrees. Both vibrators were off when the error was less. This range was selected as both a desirable and obtainable range as measured on previous GAT-1 tests. As far as the direction of motion to correct the error was concerned, both pilots who

received cuing tried both directions in a familiarization session. They both chose the vibrators mounted on their arms so that turning toward the activated vibrator instead of away from it nulled out the error. This "seeking" instead of "avoiding" strategy is similar to other instrument strategies in the cockpit. The ILS directional display and the artificial horizon are two examples.

b. Subjects

The pilots for this experiment were picked from about 15 volunteer private pilots who were members of a local flying club. Four pilots with similar flight experience and having less than 200 hours total flight time were selected from this group and paid hourly for their time. From the four pilots, two were selected at random for the cuing program and two for the control program. The four pilots selected are listed by initials and hours of flight time:

Pilot	Group
Pilot MG--90 hours	Control group
Pilot FS--35 hours	Control group
Pilot BR--100 hours	Cuing group
Pilot EW--140 hours	Cuing group

c. Procedure

Two auxiliary tasks were used to load the pilots while they were engaged in an instrument holding task. The first one--taking and repeating clearances--was designed to offer a constant load to the pilots. Approximately the same number of clearances were given per test run so that changes in pilot proficiency could be measured by the pilots' heading and altitude error scores. The second task--working simple mathematics problems--was designed to offer an increasing load to the pilots. In this way their ability to handle extra work loads could be measured in the number of problems they completed per test run. A third task measured the pilots' ability to control the GAT-1 on the same holding task without external disturbances. These three tasks are outlined in more detail below:

(1) Free Flight. After taking off and flying to 1000 feet, the pilot was requested to hold his altitude constant at 1000 feet and his heading constant at 270° while the GAT-1 was under maximum turbulence as generated by the internal rough-air system. When he arrived on altitude and heading the pilot signaled the experimenter, who started the five-minute computer monitoring program. At the end of the program the computer printed out the altitude and heading error-power scores.

(2) Clearances. The same holding condition as in free flight above except that the pilot received clearances over the GAT-1 intercom system, noted them down in his own shorthand, and repeated them back to the experimenter over the intercom. If the pilot missed any part of the clearance, the whole clearance was repeated to him again. Typical clearances used in this test are given in Appendix D.

(3) Mathematics. The same holding condition as in Item 1 above except that the pilot received simple multiplication problems verbally over the GAT-1 intercom. He took the problem down on a note pad, worked it out, and reported the answer back to the experimenter. If the answer was correct a new problem was given; if incorrect he was asked to work the same problem again. The number of problems worked successfully was recorded for later analysis. Typical math problems used are shown in Appendix D.

Each subject was tested in five two-hour sessions arranged at his convenience. The first session was a familiarization with the GAT-1 trainer, the three above conditions of the experiment, and for pilots in the cuing group, operation of the tactile cuing system. The next four sessions involved two tests with clearances, two with the math problems, and one with free flight. Pilots in the cuing group received tactile cues on one of the two math-problem tests and one of the two clearance-problem tests while those in the control group received no cuing on either pair of tests. The actual experimental design used in this experiment is given in Appendix D.

2. FREE-FLIGHT RESULTS

The error-power scores from each test were converted to root mean square (RMS) deviations (see Fig. 23). This RMS deviation (the same as the standard deviation of the errors sometimes used) is given for all four test subjects in the experiment. Figure 23 shows that all the subjects improved in both altitude and heading error over the five test sessions. The data presented in all four graphs was given an analysis of variance to determine its significant aspects. The results of the analysis are outlined below:

(1) Changes in altitude error with session are not significant [$F(4,10) = 3.13$, $p > 0.05$], while similar changes in heading error are significant [$F(4,10) = 3.86$, $p < 0.05$].

(2) There is no significant difference between cuing and control group either in altitude error [$F(1,10) = 1.74$, $p > 0.05$] or in heading error [$F(1,10) < 1$].

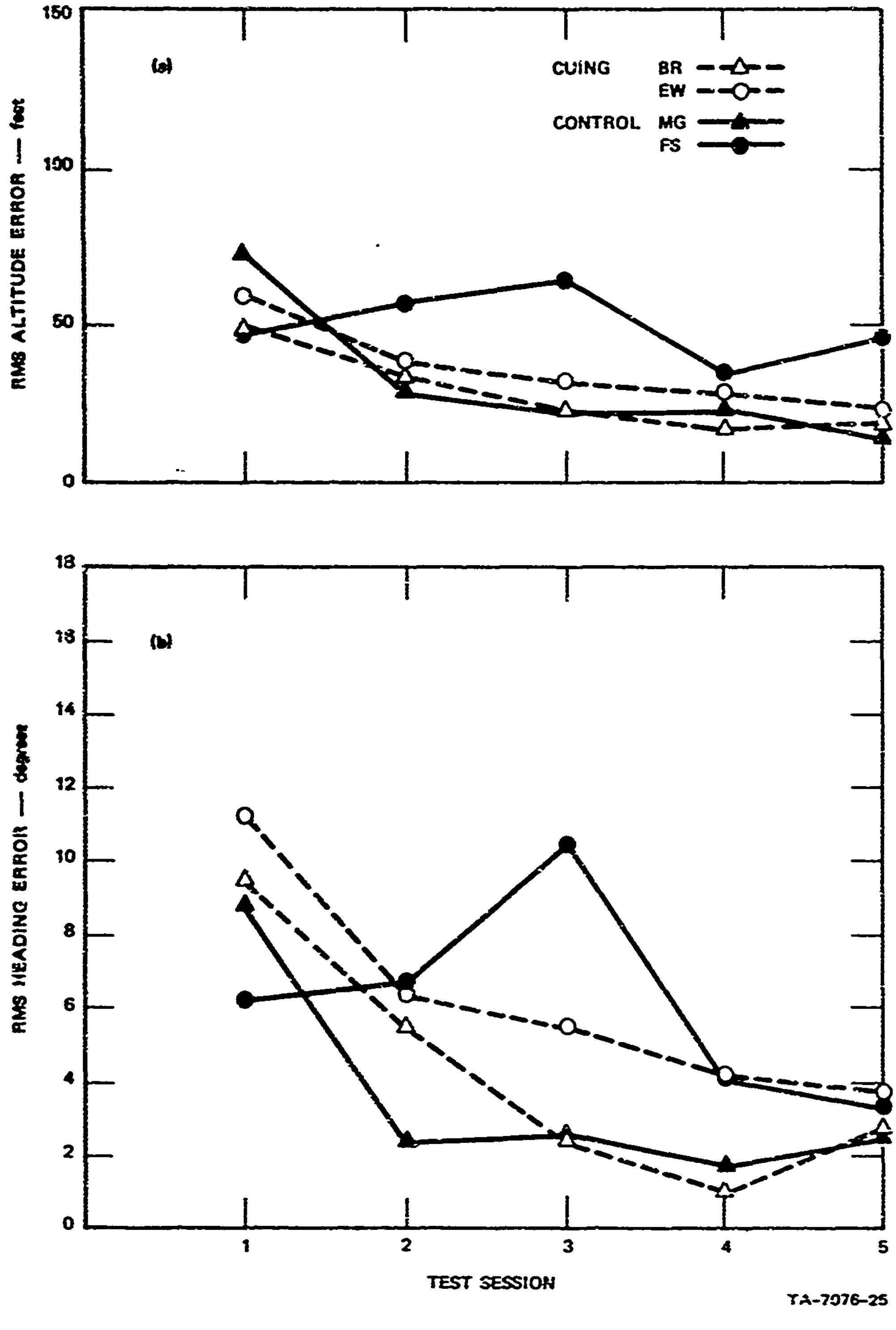


Figure 23 Comparison of the (a) RMS Altitude-Error and (b) RMS Heading-Error Scores for the Free-Flight Condition of all Four Subjects

(3) There is no significant interaction between the two groups and sessions for either heading error or altitude error, indicating that one group did not learn faster than the other.

These results indicate that the two groups were very well matched. In addition, they show that in the absence of extra work loads the tactile cuing did not quicken learning on this task or allow subjects to reach better performance levels.

3. CLEARANCE RESULTS

The RMS altitude and heading errors of both the cuing and the control groups were computed from their error-power scores and plotted in Fig. 24. Learning trends in the cuing group appear to be larger and final error scores smaller than those of the control group. The data of both cuing and control groups were given several analyses of variance to compare learning in each group and differences between the two groups. The results are summarized as follows:

(1) Both the altitude- and heading-error scores of the cuing group decreased with practice [$F(4,10) = 6.75$, $p < 0.01$ and $F(4,10) = 4.07$, $p < 0.05$, respectively], but there were no differences between sessions with and without cuing in the group.

(2) Neither the altitude- nor heading-error scores of the control group showed significant improvement with practice.

(3) The cuing-group error scores were significantly less than those of the control group in both altitude [$F(1,30) = 52.6$, $p < 0.001$] and heading [$F(1,30) = 22.5$, $p < 0.001$].

These results substantiate that in this holding task with clearances, pilots receiving the cuing progress more quickly than those in the control group.

4. MATH-PROBLEM RESULTS

The RMS altitude and heading errors for both groups are shown in Fig. 25. Again the cuing group apparently learned more quickly than the control group, but in this task the differences do not appear as great as in the clearance task. The data were given several analyses of variance to determine whether the changes and differences are significant. Only data of the last four sessions were used in the analysis since two complete tests were not made in Test Session 1. The results of the analyses of variance were as follows:

(1) Neither altitude- nor heading-error scores of either group showed any significant changes with practice.

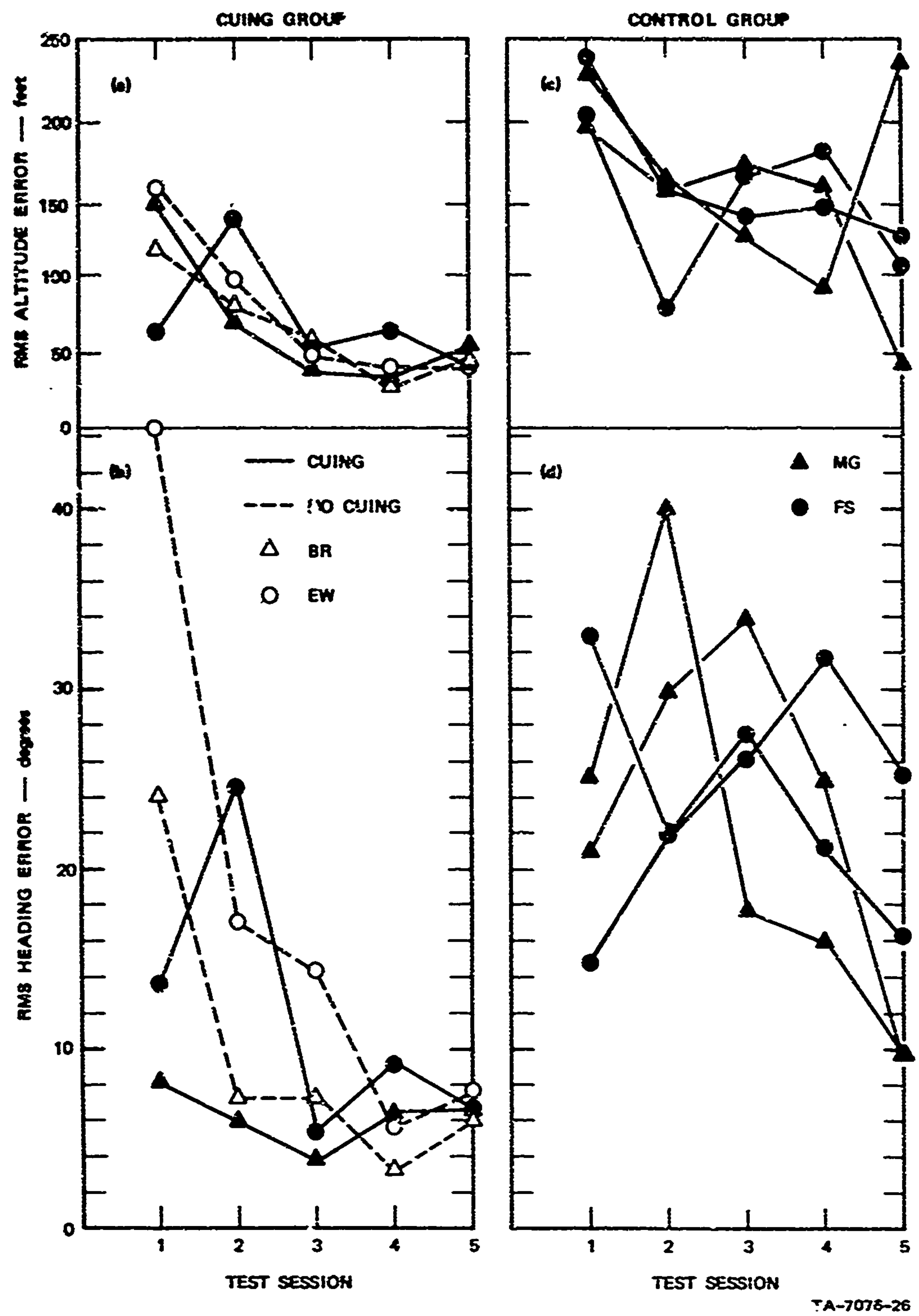


Figure 24 RMS Error Scores for Both Cuing and Control Groups Obtained from the Clearance Tests

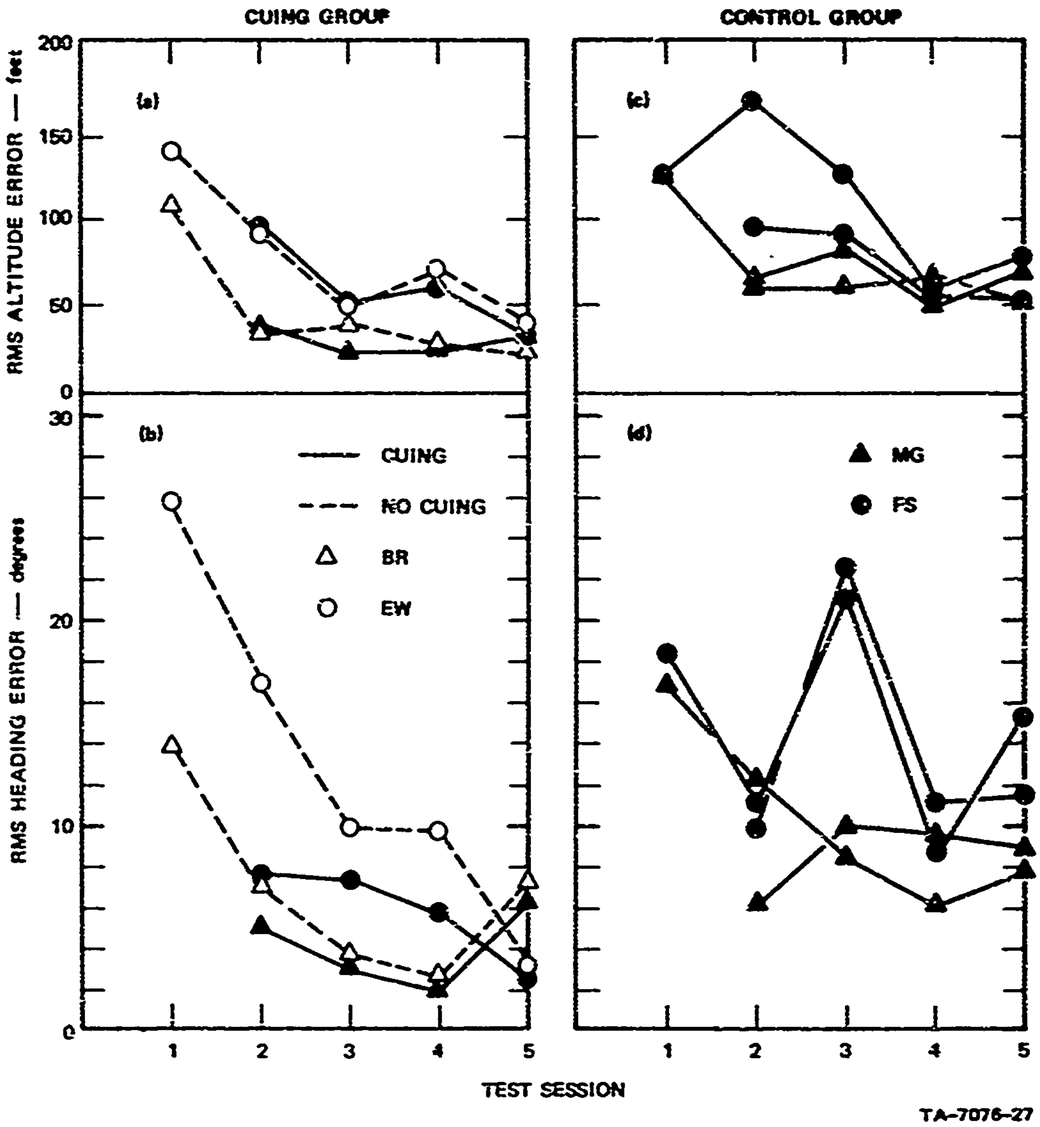


Figure 25 RMS Error Scores for Both Cuing and Control Groups Obtained from the Math Problem Tests

(2) In the cuing group there were no significant differences between errors on cuing and noncuing tests.

(3) The cuing group had significantly less error than the control group in both altitude [$F(1,24) = 124$, $p < 0.001$] and heading [$F(1,24) = 13.4$, $p < 0.001$].

The lack of significant learning by the cuing group, even though there is an apparently strong downward curve in Fig. 25, is due to the fact that only the last four sessions were analyzed. This indicates that much of the improvement occurs over the first few test sessions.

Although the number of multiplication problems worked by the pilots during the tests was originally planned as a measure of performance, there was very little change in the number of problems worked. The number of problems worked on the different test sessions by either group was not significant, nor was the number worked by the cuing group in cuing or noncuing tests (8.1 vs. 7.5 problems/test), nor the different number worked by the two groups (cuing group, 7.8 problems/test, and control group, 8.6 problems/test). The pilots evidently strove to better their flying performance while maintaining their work loads fairly constant.

5. DISCUSSION

To facilitate comparison of the three tasks used in this experiment, the data of Figs. 23, 24, and 25 has been averaged and replotted in Fig. 26. The data for both pilots and both tests within each group has been averaged together. In addition, the free flight data for both groups has been averaged together, since there were no significant differences between the groups. Comparing groups in Fig. 26 shows the difference in learning behavior, especially on heading error, the variable that drove the cuing system. The group with cuing significantly reduced their error scores with practice, while the control group maintained their initial error scores at a more or less constant level and did not significantly improve.

Comparing the three tasks in Fig. 26 shows the increasing difficulty of the free flight, math-problem, and clearance tasks. The more difficult tasks have the higher error scores and more potential room for improvement. While there was no difference between the two groups on the free flight tests, the difference grew with task difficulty. When asked after the test series was over, three of the four pilots reported that the clearance task was the most difficult.

An important question answered by this experiment is whether pilots with cuing become dependent of it for further good performance. With both the clearance and mathematics tasks there were no statistically significant differences between pilots of the cuing group when using or

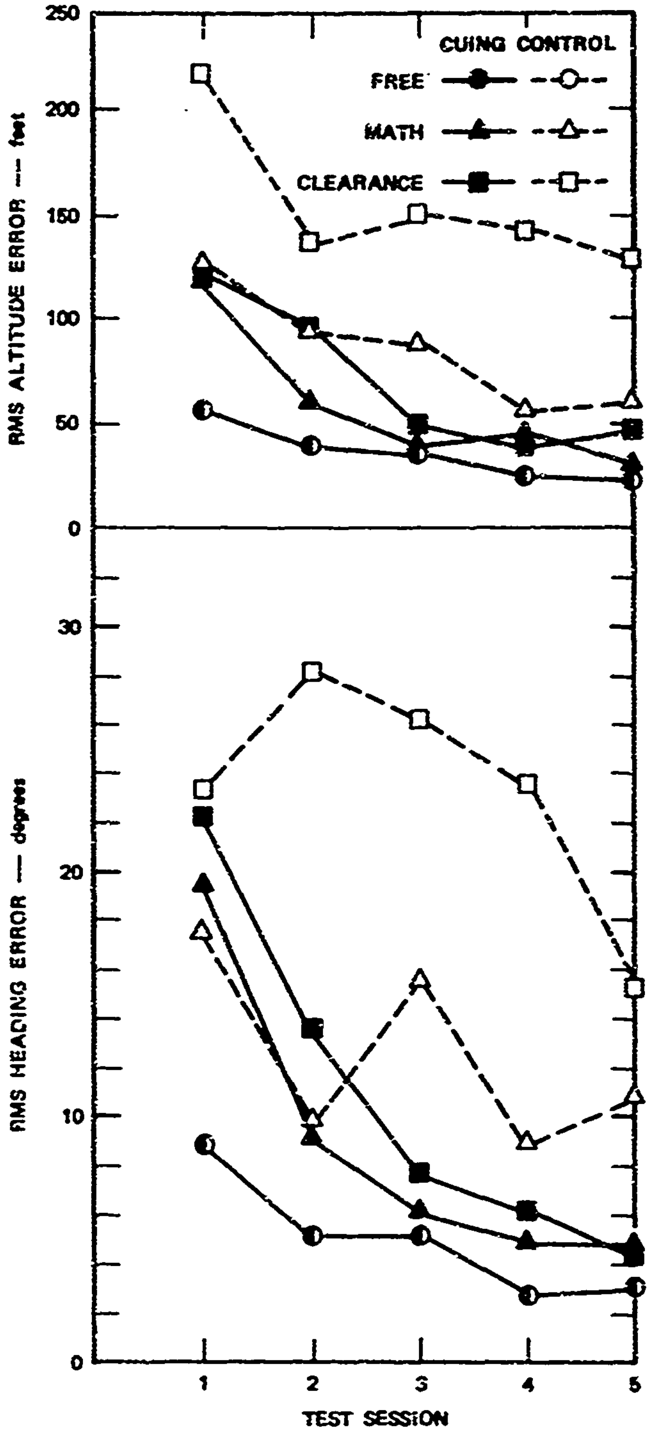


Figure 26 Average RMS Error Scores for Pilots in Both Groups with All Three Tasks

not using the cuing system. Thus, pilots in the cuing group maintained the low error scores they obtained through practice even without cuing aids.

This experiment shows an important relationship between side tasks and tactile cuing. With no side task (free flight task) there was no difference between the two groups, while with the most difficult side task (clearances) the difference in learning rate was maximum. Without a side task the tactile cuing does not influence the pilots' scores. Thus, cuing is important mainly when the pilot is loaded with work that keeps him busy while he has to control his plane. This is probably the reason why some of the preliminary display-evaluation experiments reported in Sec. V were not sensitive to cuing. Those experiments involved only a minimal side task and did not include repetitions for measuring learning.

SECTION VII

DESIGN AND EVALUATION OF A TACTILE CUING SYSTEM

As a result of the careful survey and experimental work outlined in the previous sections, we wish to express concern that the level of understanding of tactile systems and their application has not yet advanced to the point where a design for a cuing system can be proposed without any qualifications. Additional research should first be undertaken to determine:

(1) The complex relationships between visual tasks and an auxiliary tactile task in the aircraft control situation

(2) How display parameters for a given tactile display should be selected

(3) The performance difference between tactile displays mounted on the controlling body member and displays located elsewhere on the body

(4) The performance difference between displays that can be voluntarily sensed and "worn" displays

(5) How to effectively use more dimensions in tactile displays.

If, however, it is imperative that a cuing system be built and tested immediately to take advantage of the learning acceleration reported in Sec. VI, we recommend a two-stage experimental design. The first stage should essentially replicate the results of Sec. VI. Performance differences between a much larger cuing group and a much larger control group not using the one-dimensional cuing system should be made. The details of this experiment are outlined in Sec. VII-1, below, which describes Design I. Only if the learning criterion explained in Design I is met (basically a significant increase in learning rate with cuing on a loaded task) should the more elaborate cuing system of Design II be carried out. If Design II is entered and training proceeds successfully, then two control-vs.-cuing tests are recommended to measure the generality of the speeded learning with cuing. If, in addition, both of these tests are successful, as explained in Sec. VII-2 (Design II), then further implementation of the same system on a flying trainer is recommended.

It should be kept in mind, however, that these two designs represent extrapolations from state-of-the-art cuing devices and their understanding. Future work, especially in the five areas outlined at the beginning of this section, may allow tactile displays to achieve wider application or to bring about faster performance changes. Considering the present early stages of understanding in the tactile-research field and its high rate of development, it is not advisable to expend a large amount of funds in

testing and implementing the present designs without some continued and parallel basic research related to pilot training.

1. TACTILE CUING SYSTEM--DESIGN I

This design describes a one-dimensional cuing system permanently connected to one flight variable (heading) to be used in a ground-based flight trainer for substantiating the results of Sec. VI of this report using matched groups of Air Force pilots. The experiment is basically the same as that reported in Sec. IV, except that a much larger number of pilots is tested and only the most important data is obtained and analyzed. The outcome of this experiment determines whether work should be continued on Design II or dropped. The experimental design for testing this cuing system closely follows that of Sec. VI, and is indicated schematically in Fig. 27 and outlined below.

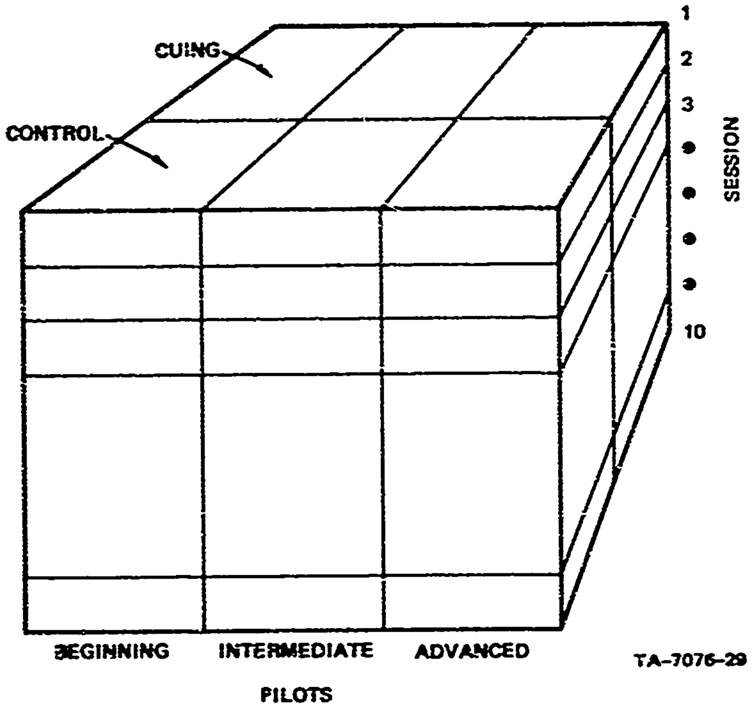


Figure 27 Experimental Design for Testing the Effectiveness of a Cuing Display

(1) Design--A two-dimensional holding task in a flight simulator should be used. Altitude and heading are highly recommended as the two dimensions, but are not necessarily the only ones that can be used. Both dimensions should include an additive random noise which the subjects try to overcome while taking the repeating clearances over an intercom system. Section IV-1-c contains further information on experimental procedure.

(2) Tactile Vibrators--Rugged vibrators capable of producing a strong feeling of vibration are required. One hundred or two hundred microns peak-to-peak vibration from 100 to 400 Hz is adequate. An inertial-type vibrator instead of the speaker-type vibrator described in Sec. IV-1-a-(1) is recommended for ruggedness. An easily adjustable elastic strap should be provided for quick attachment, adjustment, and change of body area.

(3) Cues--Cues should be given with the two threshold vibrators (see Sec. IV-1) onthe slowly varying variable (heading) such that when less than five degrees error is present no vibrator is activated, when more than five degrees right error is present the right arm vibrator is activated, and when more than five degrees left error is present the left-arm vibrator is activated. This choice of location and sign convention is discussed in Sec. VI-1-a.

(4) Subjects--At least five pilots should be selected for each experimental condition. Thus, there would be five beginners, five intermediate, and five advanced pilots in each group, or thirty pilots in all, each to be given ten sessions on the same task. Choice of pilots should be made as discussed in Sec. VI-1-b.

(5) Scoring--The RMS error of the heading-coordinate variations from the required position should be obtained by taking the square root of the heading error power.

(6) Analysis--A mixed design analysis of variance of size 2 x 3 x 10 x 5 (groups by pilot experience by sessions by pilots) should be made on the above heading-error scores. The crucial test for success is the session-by-group interaction. If this interaction is significant (5 percent test) and the cuing group learned faster than the control group, then proceed to Design II. If, in addition, the session-by-group-by-pilot experience interaction is significant (5 percent test), sorting the cuing-vs.-session results by pilot experience will show which experience groups most efficiently utilize cues. In this case Design II should be continued only with this best group.

2. TACTILE CUING SYSTEM--DESIGN II

This design describes the implementation of an extended, seven-variable cuing system in a ground-base trainer, and outlines training and testing procedures to evaluate it. Two key tests are recommended after a group of pilots have learned to use the system. If these tests, involving ILS landing and cross-country navigation are successful, measured with the criteria of Design I, then further implementation of the system on one trainer airplane is recommended; if the tests are not successful, the system should be dropped. The experimental design for testing this extended cuing system closely parallels that of Design I, and is described below:

(1) Tactile Vibrators--Same as recommended for Design I.

(2) Source Switch Box--For reference-signal selection the cuing system should contain a multiple-position switch operable by either the instructor or the student pilot. The selector switch should be able to connect the two vibrators to any of the following reference signals in the trainer:

ILS Glide Slope, $\pm 5°$ cues
ILS left-right, $\pm 5°$ cues
ADF left-right, $\pm 5°$ cues
Air speed--adjustable speed center, ± 5 mph cues
Altitude--adjustable altitude center, ± 50 feet cues
Heading--adjustable heading center, $\pm 5°$ cues.
Rate of climb--adjustable rate center, ± 50 feet/min cues.

Selecting a switch position and turning one knob to the reference position is all the work that should be required. The internal cuing limits should be internally wired so that within the dead zone there is no vibration and outside the zone only the one appropriate vibrator is full on.

(3) Training Procedure--Training along the following lines is recommended before use of the cuing system. First the student should be familiarized with the general idea of the cuing system by both explanation and demonstration of one-dimensional holding. Secondly, he should be tested on each holding coordinate by temporarily covering the basic visual instrument and watching to see that he holds that coordinate within the cuing limits. Lastly, several complete practice runs such as an ILS landing using airspeed or left-right cuing or an altitude-holding run using the altitude cues should be carried out.

(4) Implementation Schedule--The cuing system should first be implemented in a fixed-base trainer and given further testing by pilots trained with the cuing system as described above. If

enough pilots freely and voluntarily use the system, then two additional, controlled experiments should be carried out to further compare a control group and cuing group. Both of these experiments use the format of Design I; only the task is changed. The first experiment should be an ILS landing approach with airspeed cuing requiring the pilot to contact the control tower and to work an ETA problem as a side task. The second experiment should be cross-country navigation using the ADF with left-right cues, requiring the pilot to work a navigation-type problem of similar complexity on each run for a side load. The experimental design and evaluation should be carried out using at least 20 pilots (equal numbers in the cuing and control groups), as in Design I, but lumping pilots of mixed experience together. If both of these results are successful as specified in the first test of Design I, further implementation of the same system in a trainer-type airplane for use in flight situations is recommended. If a trainer is used in this way, particular emphasis should be placed on developing ILS landing approaches with the system.

APPENDIX A

INTERFACE CIRCUITS BETWEEN THE GAT-1 TRAINER AND LINC-8 COMPUTER

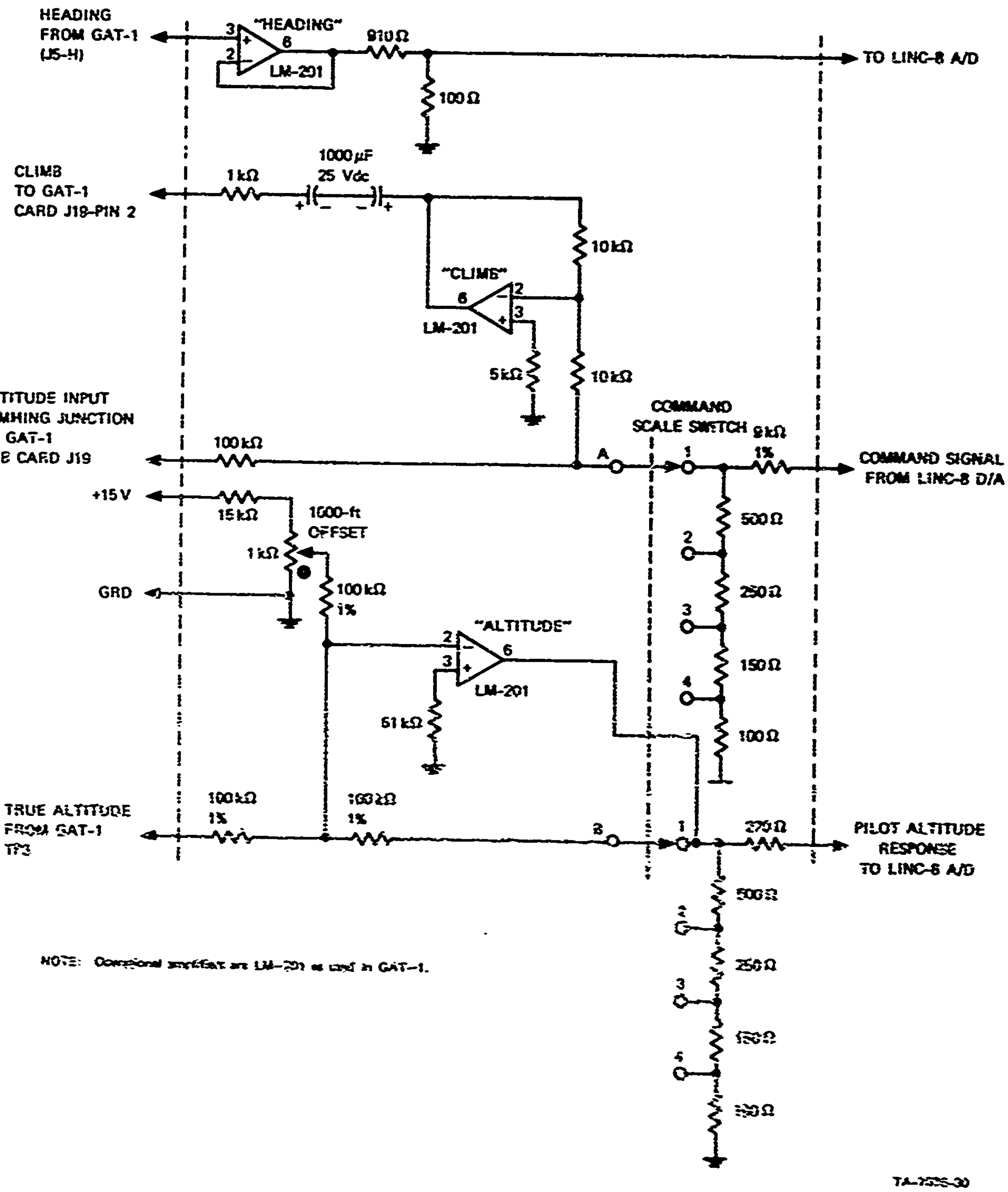
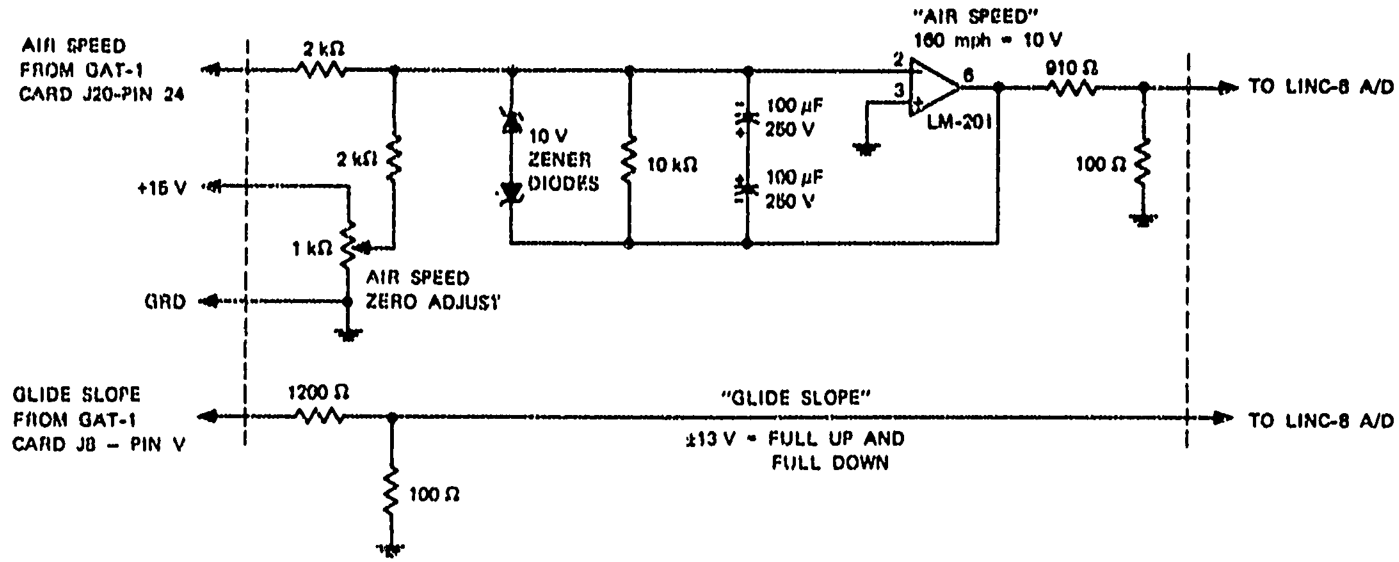


Figure A-1 Altitude-Tracking-Interface Circuit



NOTE: Operational amplifier is LM-201.

TA-7076-31

Figure A-2 Airspeed and Glide-Slope-Interface Circuit

APPENDIX B

DESCRIPTIONS OF THE GAT-1 DISPLAY EVALUATION EXPERIMENTS

APPENDIX B

DESCRIPTIONS OF THE GAT-1 DISPLAY EVALUATION EXPERIMENTS

EXPERIMENT CAH

Hold constant altitude and heading

Program GATKO (GARTKO for air jets)

Run Time: 5-1/4 minutes
Monitor: altitude and heading
Display Gain: 0.5 volt (133 feet) full scale
Tactile Signal: CAH-A designation for altitude cue (primary signal)
CAH-H designation for heading cue (secondary signal)

Sequence of Events

(1) Pilot takes off and flies to 1000 feet; trims plane for level flight at 110 mph (TACH = 2400) at heading of 270°. Maintains heading and altitude constant throughout this run.

(2) Experimenter starts LINC-8 program, defines time as time zero.

(3) After 30 seconds from time zero, pilot reduces power (to TACH = 1700) and continues without changing altitude or heading.

(4) At 2 minutes from time zero, pilot increases power (TACH = 2400).

(5) At 3-1/2 minutes from time zero, pilot decreases power (TACH = 1700).

(6) At 5 minutes from time zero, pilot increases power (TACH = 2400).

EXPERIMENT AT

Altitude tracking

Program GATK1 (GARTK1 for air jets)

Run Time: 5-1/4 minutes
Monitor: Altitude and heading
Command Signal: 350 feet peak altitude change
Display Gain: 0.25 volt (66 feet) full scale
Tactile Signal: AT-A designation for altitude cuing
AT-H designation for heading cuing

Sequence of Events

(1) Pilot takes off and flies to 1000 feet on heading 270° (due west). Trims plane for level flight at 100 mph.

(2) Experimenter starts LINC-8 program.

(3) Pilot continues flying, holding altitude constant at 1000 feet and heading at 270°. Pilot uses throttle control to avoid stall and overspeed conditions when necessary.

EXPERIMENT CS

Holding constant airspeed while making instrument landing with ILS system

Program GATKO (GARTKO for air jets)

Run Time: 5-1/4 minutes
Monitor: Airspeed and glide slope
Display Gain: 0.25 volt (5 mph) full scale
Tactile Signal: CS-S designation for airspeed cue (primary cue)
CS-GS designation for glide-slope cue (secondary cue)

Sequence of Events

(1) Pilot takes off and flies to 2000 feet on heading 288°. Trim plane for level flight at 85 mph.

(2) Experimenter positions airplane near center of beam 10 miles from airport. Pilot flies to the left-right beam first; then, when he crosses the glide-slope beam the first time the experimenter starts the LINC-8 program.

(3) Pilot flies down beam while maintaining airspeed at 85 mph and keeping the ILS indicator zeroed.

APPENDIX C

PILOT RANKING AND COMMENTS ON THE FIVE TACTILE DISPLAYS

APPENDIX C

PILOT RANKING AND COMMENTS ON THE FIVE TACTILE DISPLAYS

Following the experiments of Sec. V the three pilots were given questionnaires asking them to rank the five tactile displays and give comments on each of them. Their rankings and comments are given in this appendix.

Device	Rank Ordering 1 = Best 5 = Worst	Comments (Adequacy, use during training, ease of interpreting, etc.)
	COMMENTS ON TACTILE CUING DEVICES--PILOT BD	
Air Jets	2	Cuing not strong enough. Difficult to distinguish between senses of cue.
Linear Vibrator	—	Pilot did not use display.
Threshold Vibrator	1	Good indicator. Threshold devices most useful (provided "off" range wide enough).
Thumb Button	4	Difficult to detect. Had to move thumb back and forth.
Palm Button	3	Difficult to detect. Good cue for altitude if more detectable.
Note: All cues involving the left-hand were difficult to detect due to tight grip on wheel.		
	COMMENTS ON TACTILE CUING DEVICES--PILOT CR	
Air Jets	3	Good for alerting subject to some conditions. The direction of the error was sometimes difficult to interpret.
Linear Vibrator	2	Adequate for most uses. Particularly good for displaying errors that vary widely. Not useful for errors the subject is already holding within small tolerances.
Threshold Vibrator	1	Very good for alerting subject. Particularly good for signals that change very slowly and thus should not require much visual monitoring. Direction indications very good.
Thumb Button	4	Needed more travel to be adequate. Had to be actively monitored by subject. Not very alerting.
Palm Button	5	Had to be actively monitored by subject. Failed to alert subject to extreme conditions.
	COMMENTS ON TACTILE CUING DEVICES--PILOT TH	
Air Jets	5	Little or no resolution between "up" and "down" signals. No indication that either intensity or position changed with increasing error (gain too low?).
Linear Vibrator	3	Sensitivity lost after initial error signal has been on for more than a few seconds. Some difficulty sensing polarity; it was not immediately apparent which buzzer was on.
Threshold Vibrator	4	Same problems as the linear vibrator; no information in the dead band suggests increased error rates.
Thumb Button	1	This display had all the prerequisites of a useful aid: gain high enough, or adjustable, very small dead band, ease of thumb motion allows initial sensitivity level to be maintained, and very definite polarity sensing.
Palm Button	2	Same as for the thumb button, except for loss in sensitivity due to lack of motion ease; also, the position of the display made adequate contact uncomfortable and thus detracted from its general performance level.

APPENDIX D

DESIGN OF A PRELIMINARY EXPERIMENT TO TEST A TACTILE CUING SYSTEM

APPENDIX D

DESIGN OF A PRELIMINARY EXPERIMENT TO TEST A TACTILE CUING SYSTEM

The experimental design used in Sec. VI is given in Table D-1. Each test run is five minutes long. Sample clearances and mathematics problems are given in Tables D-2 and D-3. The mathematics problems require the multiplication of a two-digit random number, A, by a three-digit random number, B, to get the answer shown in column A x B of Table D-3.

Table D-1

TEST SCHEDULE FOR CUING-SYSTEM EXPERIMENT

SUBJECT______________________________

FLIGHT EXPERIENCE (HR)______________

	Run 1	Run 2	Run 3	Run 4	Run 5
Session 1 Familiarization with GAT-1 and Experiment	Level	Clearance	Math	Clearance Cuing	
Session 2 Test	Clearance Cues	Clearance	Math Cues	Math	Level
Session 3 Test	Clearance	Clearance Cues	Math	Math Cues	Level
Session 4 Test	Clearance Cues	Clearance	Math	Math Cues	Level
Session 5 Test	Clearance	Clearance Cues	Math Cues	Math	Level

Rough Air Always Full On. Fog covers on windows.

Level = Flight at 1000-ft altitude, 270° heading

Clearance = Same as level; pilot takes and repeats approximately three clearances

Math = Same as level; pilot to work math problems continuously

Cues = Heading cuing on arm vibrators

Table D-2

SAMPLE CLEARANCES

(1) LINK 1234 CLEARED FOR TAKEOFF, TURN LEFT AFTER DEPARTURE TO HEADING 240, CLIMB ON COURSE TO FIVE THOUSAND, REPORT FIVE THOUSAND TO DEPARTURE CONTROL, FREQUENCY WILL BE 121.1.

(2) AIR TRAFFIC CONTROL CLEARS LINK 1234 TO THE WASHINGTON AIRPORT VIA VICTOR 14 SOUTH, CROSS SHAUGHNY INTERSECTION FIVE THOUSAND, MAINTAIN SEVEN THOUSAND TO THE BUNKY INTERSECTION, DESCEND TO THREE THOUSAND ON HEADING 197 AND CONTACT TOWER ON 123.2.

(3) ATC CLEARS LINK 1234 TO THE SKYLINE AIRPORT VIA THE CROSSVILLE 055 RADIAL VICTOR 18, MAINTAIN FIVE THOUSAND, CLEARANCE VOID IF NOT OFF BY 1330.

Table D-3

TWENTY SAMPLE MULTIPLICATION PROBLEMS

Problem Number	A	B	A X B
100	25	360	9000
101	94	745	70030
102	42	756	31752
103	81	705	57105
104	62	902	55924
105	16	759	12144
106	64	587	37568
107	57	697	39729
108	26	500	13000
109	93	308	28644
110	18	430	7740
111	13	280	3640
112	18	166	2988
113	65	402	26130
114	95	398	37810
115	50	464	23200
116	49	913	22737
117	35	255	8925
128	38	602	22876
119	89	464	41296

APPENDIX E

SELECTED BIBLIOGRAPHY ON BIOSTIMULATION AND BIOELECTRIC CONTROL

APPENDIX B

SELECTED BIBLIOGRAPHY ON BIOSTIMULATION AND BIOELECTRIC CONTROL

A preliminary review of the literature and current research was carried out to assess the feasibility and appropriateness of biostimulation and bioelectric control for pilot training and aircraft control. For this purpose the area under study was defined as electrical stimulation to produce either a muscular response or a sensation.

The papers, reports, and conferences reviewed are listed below in five categories.

1. BASIC PHYSIOLOGY OF CONTROL OF MOVEMENT (Reference books and current research on the neurological mechanisms that control movement in humans)

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Zajac, F. E., "The Mathematical Formulation of the Kinematic Properties of Muscle Derived from an Experimental Investigation," Ph.D. Dissertation, Stanford University, Neurological Sciences (August 1968).

2. CONTROL BY BRAIN STIMULATION

Delgado, J. M., "Sequential Behavior Induced Repeatedly by Stimulation of the Red Nucleus in Free Monkeys" Science, Vol. 148, pp. 1361-1363 (1965).

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3. EXTERNAL CONTROL OF HUMAN EXTREMITIES

Alter, R., "Bioelectric Control of Prosthesis," MIT-RLE Technical Report 446, Contract DA-36-039-AMC-03200(E) (1 December 1966).

"Some Topics on Myo-Electric Control of Orthotic/Prosthetic Systems," L. Vodovnik, Ed., Report No. EDC 4-67-17, Case Western Reserve University, Cleveland, Ohio (1967).

Glenn, W. W., A. Mauro, and A. S. Chao, "Remote Stimulation by Radio-Frequency Transmission," Public Health Service Project No. HE 04651-09, Yale University School of Medicine, 333 Cedar Street, New Haven, Connecticut (1968).

Quast, J. E., and M. S. Seeger, "Studies in Neuromuscular Facilitation," VA Project No. 73-67, V. A. Hospital, Minneapolis, Minnesota (1967).

Steinberger, W. W., and E. M. Smith, "Stimulus Programming for Work in Denervated Muscle," Public Health Service Project No. AC1/NB 07081-02, University of Michigan, Ann Arbor, Michigan (1968).

Waring, W., "Investigation of Myoelectric Control of Functional Braces," Final Report, Research Grant No. RD-1751-M, Dept. Health, Education, and Welfare, Rancho Los Amigos Hospital, Downey, California (1968).

External Control of Human Extremities, The Proceedings of the International Symposium, Dubrovnik, 29 August-2 September 1966, Yugoslav Committee for Electronics and Automation, Belgrade (1967).

4. TRAINING EFFECTS

Carrow, R. E., et al., "Effects of Voluntary and Electrically Forced Training," Public Health Service Project No. 5 R01 GM 12261-03, Michigan State University, East Lansing, Michigan (1967).

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Gibson, R. H., "Electrical Stimulation of the Skin—A Selected Bibliography," issued by IRIS, American Foundation for the Blind, Inc., New York, New York (July 1967).

As a result of this preliminary review, the following tentative conclusions were reached:

(1) Electrical stimulation with skin electrodes near the periphery for control of movement appears to be a difficult task requiring further development before immediate application in the training situation should be attempted.

When one considers that at the spinal level, each muscle has associated with it a pool of thousands of alpha motor neurons, at least two systems of sense-organ-controlling motor cells, the static and dynamic gamma neurons, three classes of receptors

involving several hundred channels of input information to the cord, and associated clusters of interneurons that serve to integrate, distribute, and modify the activity within the cord and the control loops by which communication with the muscle is effected, it is easy to understand why bypassing this system by simply applying a control signal directly to the muscle will not produce precise controlled movements. Moreover, most movements involve many muscles, not just one.

(2) If this peripheral nervous system is not bypassed and the input signal is applied directly to the appropriate regions of the brain, then smoother, more complex movements can be obtained. However, this method is impractical for application in the training situation.

(3) Recent results from basic studies in muscle physiology (e.g., Zajac, 1968, and Leifer, 1969) suggest new approaches for acquiring control signals from muscle in man and for injecting control signals into muscle. For example, Leifer's experiments show that, at least under isometric conditions, muscle tension is controlled by muscle-fiber recruitment rather than frequency of firing of the motor neurons. This result has implications in the design and placement of electrodes and in the form of signal processing to be used. However, these basic studies need to be extended to cover a wider range of conditions (e.g., other than isometric) before immediate application can be made.

(4) Electrical stimulation for cuing, either by producing sensation or by causing a muscle twitch, is feasible. But the relative advantages and disadvantages of these techniques must be weighed against other alternatives, such as tactile cuing. Further investigation should help verify and clarify these points so that reasonable decisions can be made. Meanwhile, it is our opinion that at this point in time, tactile cuing offers greater promise than electrical stimulation.

(5) Brindley's results with cortical stimulation are very surprising, and further work in visual prosthesis should be watched for possible application. However, in view of the potential dangers involved, it is likely to be quite some time before this research has reached the point that application will be warranted, if it ever does.

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13. ABSTRACT

Several vibrator, air jet, and moving-button tactile stimulator-units were evaluated as cuing aids for pilot training in a manual tracking task. The best units, as determined by minimum mean square error and best operator describing function were built into a flight simulator. These units were further evaluated for their ability to help pilots control the trainer in some flight-simulation tracking tasks such as altitude holding and ILS landing. A one-dimensional tactile cuing system was designed using information obtained from these experiments. The cuing system, which consisted of two vibrators attached to the arms indicating heading error in excess of five degrees, was tested in a controlled experiment with four pilots having less than 200 hours of flight time. ~~The two pilots using the cuing system learned signifi-~~ cantly faster than the two pilots not using the system. This increased learning rate, however, was only seen when the pilots were engaged in side tasks such as problem solving and the taking of clearances. Plans for a more complete test of this cuing system and for possible extensions of the cuing system to other aircraft variables are suggested. A selected review of the literature and current research was carried out to assess the feasibility and appropriateness of biostimulation and bioelectric control for pilot training and aircraft control.

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